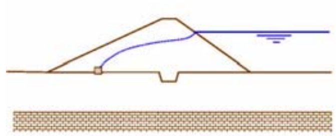
INDIANA DAM SAFETY INSPECTION MANUAL

PART 2



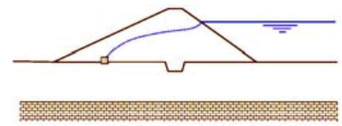
DAM MANAGEMENT AND MAINTENANCE

2003 EDITION

Department of Natural Resources
Division of Water
Indianapolis, Indiana

INDIANA DAM SAFETY INSPECTION MANUAL

PART 2 DAM MANAGEMENT AND MAINTENANCE



2003 EDITION

Preface

The Indiana Dam Safety Inspection Manual is based on accepted practice and consists of information developed from existing documentation on dam safety inspections obtained from state and federal agencies. Dam safety is a complex and multi-disciplinary practice that continues to evolve as professionals gain a better understanding of how the various dam components behave under different loading conditions and how society's level of risk tolerance changes with time. This manual is a "living document" that will change to reflect evolving national practice. As this manual improves with time, it will provide a stable reference for good dam safety inspection practice as administrators, program priorities, and statutes change. It consists of four separate parts:

Part 1 of the Manual describes ownership responsibilities and roles, risks and hazards of dam failure, and provides a detailed overview of dams in Indiana.

Part 2, this part, presents guidelines for operating and maintaining a dam, including specific instructions on how to prepare a management and maintenance plan and how to respond to emergencies.

Part 3 provides guidance on evaluating dam safety and performing dam inspections. It covers who should perform the inspections and how, and provides guidance on identifying and reporting dam deficiencies and problems.

Part 4 is a compilation of Dam Safety Fact Sheets that present information on a variety of dam operational issues, such as seepage, slope protection, embankment stability, and spillway design, to name a few.

This manual should not be used in lieu of appropriate dam safety technical courses or training by a dam safety professional in the area of dam inspection. However, it should be used by experienced dam safety professionals as a reference and reminder of the aspects required to make a thorough dam safety inspection and evaluation. It should be stressed, however, that inspections alone do not make a dam safe; timely repairs and maintenance are essential to the safe management and operation of every dam.

The dam owner is responsible for maintaining the dam in a safe condition, and should do whatever is necessary to avoid injuring persons or property. As once stated by a highly respected legal scholar, "It is clear that compliance with a generally accepted industry or professional standard of care, or with government regulations, establishes only the minimal standard of care. Courts may assess a higher standard of care, utilizing the "reasonable person" standard and foreseeability of risk as the criteria. It is fair to say that persons who rely blindly upon a governmental or professional standard of care, pose great danger to others, and present a legal risk to themselves, when they know or reasonably should know that reasonable prudence requires higher care."

This manual was prepared by:

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Acknowledgements and Disclaimer

This Manual was developed by Christopher B. Burke Engineering, Ltd. (CBBEL) for the Indiana Department of Natural Resources (IDNR), Division of Water. Principal editors, authors, and support staff within CBBEL included: Siavash E. Beik, P.E. (Project Manager & Technical Editor), Ken Bosar, P.E. (Principal Author), and Jon Stolz, P.E. (Technical Consultant). Principal reviewers and project coordinators at the Division of Water included Kenneth E. Smith, P.E. (Assistant Director) and George Crosby, P.G. (Manager, Dam and Levee Safety Section).

A four-member peer review team provided technical review and advice during the preparation of the manual. The team members included Charles Rucker P.G., Robert Biel, P.E., Thomas Hugenberg, P.E., and John Pfeifer, P.E., all former Army Corps of Engineers dam safety professionals.

Much of the material presented in the manual was adapted from various publications developed by Federal and State agencies for dam inspection, operation, and maintenance. In many cases, pertinent text and illustrations were directly utilized within the manual with permission. A complete list of these publications is provided in the Appendices under References. The photographs were primarily obtained from IDNR and CBBEL files for Indiana dams; some photographs were obtained from public sources. The following is a list of agencies whose publications were extensively used in the preparation of this manual:

Indiana Department of Natural Resources
Association of State Dam Safety Officials
U.S. Army Corps of Engineers
U.S. Department of Agriculture Natural Resources Conservation Service
U.S. Department of the Interior, Bureau of Reclamation
Wisconsin Department of Natural Resources
Ohio Department of Natural Resources
Colorado Division of Water Resources
Pennsylvania Department of Environmental Protection

Special recognition is given to the Federal Emergency Management Agency (FEMA) who provided funding to the IDNR for the development of this manual. Special recognition is also given to the Association of State Dam Safety Officials (ASDSO) for their leadership in developing effective dam safety programs and policies for the furtherance of dam safety. Their diligence in assisting the U.S. dam safety community was an important factor in the issuance of the FEMA grant.

Use of trade names, brand names, or drawings designating specific products is for reference purposes only and does not constitute an endorsement of products or services by CBBEL, review team members, the State of Indiana, or any of the cooperative agencies/organizations. Information describing possible solutions to problems and concerns, repairs, and emergency actions are intended for guidance only. The dam owner should seek qualified professional help for construction of new dams and extensive remedial measures for existing dams. Site-specific plans, emergency actions, and repair procedures should be developed on a case-by-case basis; CBBEL, review team members, the State of Indiana, any of the cooperative agencies/organizations and references cited assume no responsibility for the manner in which the contents of the Manual are used or interpreted, or the results derived therefrom. Current IDNR regulations pertaining to dams should take precedence to information contained within this Manual.

Indiana Dam Safety Inspection Manual
Comments Form

Although significant effort went into the completeness and accuracy of this manual, it is recognized that some information may not reflect all the various practices or viewpoints held by all dam safety professionals. In a document of this size, it is further acknowledged that there may be errors, or worse yet, a misleading phrase that would diminish the desired result of dam safety. The contributors of this manual encourage dam safety professionals to provide comments to the Indiana Department of Natural Resources, Division of Water to help improve and keep this manual up-to-date.

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PART 2 DAM MANAGEMENT AND MAINTENANCE

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CHAPTER 1.0

INTRODUCTION

1.0 INTRODUCTION

Part 2 of the Indiana Dam Safety Inspection Manual presents guidelines for preparing an Management and Maintenance (M&M) Plan for a dam, and includes typical procedures for operating and maintaining a dam and its appurtenant works.

Chapter 2 (Part 2) describes the elements that should be contained in a complete M&M Plan. The purpose of preparing and implementing a dam M&M Plan is to provide the greatest possible assurance of the safety of the dam and continuous operation of the reservoir. An effective plan provides all the information and instructions needed to allow an inexperienced person to perform the actions required to operate the dam safely. The items addressed in the plan should include pertinent background data, operation of appurtenant structures, periodic inspection of the dam, monitoring the dam's performance, recording and interpreting the results of the inspection and monitoring, and performance of all required maintenance. The M&M Plan should not include the detailed procedures for performing dam inspections, monitoring, and maintenance, but rather, should include instructions, forms, and schedules for implementing the detailed procedures. Assembling the required information and writing a site-specific M&M Plan is the responsibility of the dam owner/operator.

Chapters 3 and 4 of this Part describe the typical Management and Maintenance procedures that may be implemented as part of the plan. Part 3 of the Indiana Dam Safety Inspection Manual covers detailed inspection procedures that may be followed as part of the M&M Plan.

A well prepared M&M Plan can help the dam owner:

- assure the safety of the dam and continuous operation of the reservoir,
- minimize legal and financial liability,
- avoid the waste of stored water by having it under control at all times,
- minimize the need for costly repairs, and
- extend the useful life of the structure.

Dam inspection and maintenance are two key components of the M&M Plan. In most cases, dam failure can be prevented if the structures are properly maintained. Dams are man-made structures which must be designed, inspected, operated, and maintained. Maintenance is an ongoing process that not only involves such routine items as mowing the grass and clearing the trash rack, but also includes regularly inspecting the structure and properly operating its components. It is usually more cost effective to implement maintenance repairs than it is to repair a dam after failure of a critical feature (i.e., embankment, spillway). Major rehabilitation of a dam should not be necessary if the dam was designed in accordance with good engineering practice, was built using good construction standards, and is operated and maintained properly.

CHAPTER 2.0

MANAGEMENT AND MAINTENANCE PLAN

2.0 MANAGEMENT AND MAINTENANCE PLAN

2.1 OVERVIEW

The extent of an M&M Plan is dependent on the type, complexity, and hazard classification of the dam. Contributing factors include dam size, number and type of appurtenances, the number of operable mechanisms, and the risk imposed on downstream areas in the event of a dam failure. For example, a high hazard dam may require more frequent safety inspections, and very detailed emergency procedures. The most effective plans are usually the simplest that are easy to implement. M&M Plans will need to be reviewed and updated on a regular basis to incorporate changes or revisions to the information in the plans.

An effective M&M Plan includes three principal parts: (1) Background Data, (2) Routine Procedures, and (3) Emergency Procedures. The M&M Plan should be in writing in order to provide the owner with a logical set of instructions to follow. If well organized, this information can easily be passed on to future owners. The operation plan should provide for limited access to spillway controls, and locks on all fencing, valves, and mechanical equipment.

Table 2-1
Outline of Typical Dam M&M Plan

1. **Background Data**
   - Vital statistics
   - Important phone numbers
   - Site plan
2. **Routine Procedures**
   - Spillway, outlet & reservoir operating instructions
   - Inspection instructions, forms, and schedules
   - Monitoring instructions, forms, and schedules
   - Maintenance instructions, forms, and schedules
   - Security and safety requirements
3. **Emergency Response Procedures**
   - Identification of hazard area
   - Identification of emergency and potential risks
   - Notification procedures
   - Available resources
   - Emergency repair procedures

Background Data is a listing of pertinent dam data, or vital statistics, that describe important features of the dam and the address and telephone numbers of key personnel. A typical dam owner/operator possesses a large amount of information about his/her facility; Part 3 describes the information that should be contained in the dam owner's project files and information database. Background Data is a synopsis of the information contained in the owner's files and should be contained on one sheet of paper so that it is available for quick reference. Background Data should also include a site plan, which is a map or sketch of the dam and its appurtenant works showing all important features. Appendix A, Part 2, contains a sample Background Data Sheet that can be used in a typical dam M&M Plan.

Routine Procedures should include: operation procedures for dam features and appurtenances; inspection instructions, schedules, and checklists; instrumentation and monitoring instructions; maintenance instructions and schedules; and security and safety requirements. The instructions should identify the features that need to be inspected, monitored, and maintained, as well as any special considerations. The detailed procedures for performing inspections and maintenance should not be included in the M&M Plan. The schedules should include both day-to-day tasks, tasks performed less frequently through a given year, and preventive maintenance activities. The schedules serve to formalize inspection and maintenance procedures such that an inexperienced person could determine when a task is to be performed by consulting the M&M Plan.

The Emergency Procedures part should contain a formal plan for reacting to dam emergencies, especially if the dam has a high hazard classification. It should define coordination between the dam owner/operator, local agencies and downstream residents, as well as procedures for dealing with the emergency.

Part 2 of the Indiana Dam Safety Inspection Manual is intended to serve as a guide to assist the dam owner/operator in preparing and implementing an M&M Plan. Additional assistance from a qualified dam safety professional may also be helpful.

2.2 BACKGROUND DATA

Background Data is a list of key elements of the dam and reservoir design and operating parameters. These parameters are often referred to as the dam's vital statistics. Ideally, the vital statistics are contained on one sheet of paper which can be used as a quick reference during operation, maintenance, and emergencies. Prior to assembling the Background Data, the dam owner/operator will need to gather all the information in his/her possession regarding the dam. Examples may include design reports, photographs, plans, maps and miscellaneous correspondence pertaining to the facility. A site plan consisting of a topographic map (if available), or a dam sketch should be attached to the Background Data Sheet. Appendix A contains a sample Background Data Sheet that can be used. All of this information should be part of the dam information database contained in the owner's project files.

Maps, plans, and other sources should be reviewed for dimensions and descriptions that will provide a clear picture of the location, makeup, and function of each part of the dam. Especially important are:

1. Overall dimensions of the dam

Table 2-2
Suggested Contents of Background Data Sheet

1. General Information
- owner address & phone no.
- county location
- township location
- stream name
- year completed
- hazard classification
- important telephone numbers
- significant problems in the past

2. Dam and Embankment
- type of dam
- height of dam
- length of crest
- width of crest
- angle of upstream slope
- angle of downstream slope
- available freeboard
- top of dam elevation

3. Spillway
- type and dimensions of spillway
- dimensions of spillway crest
- spillway crest elevation
- normal pool elevation
- available freeboard
- greatest depth & date of occurrence
- design capacity
- discharge channel

4. Outlet (if present)
- size and type of outlet
- size and type of outlet control device
- inlet invert elevation
- outlet invert elevation

5. Monitoring Devices (if present)

6. Hydrology and Hydraulic Data
- maximum capacity of dam
- design storm event
- design storm flow
- reservoir stage-storage tables
- reservoir stage-discharge tables
- time of concentration
- watershed area

2. Spillway configuration and operation
3. Outlet configuration and operation
4. Drainage systems and outfall locations
5. Location and detail of monitoring points
6. Capacity tables for the reservoir
7. Discharge tables for the outlet and spillway
8. Location and capacity of inflow and outflow ditches
9. Records of past inspections, monitoring, repairs, and operating problems
10. Photographs of pertinent features or problems on the dam, taken annually and kept on file for comparison and reference.

If a detailed set of drawings for the dam does not exist, a plan or sketch, and representative cross sections should be drawn up. If a dam was constructed with a detailed topographic map with grading plans, this may be used to depict the key features. However, many dams were constructed without plans, or have no plans at all. If the dam is relatively large, has maintenance and repair concerns, or is a high hazard dam, a survey of existing conditions and features may need to be performed and a topographic map prepared.

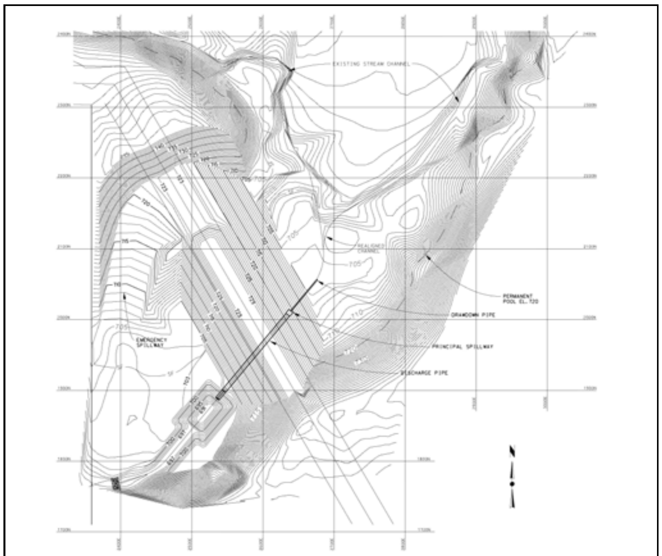

Figure 2-1 Grading plans for a small embankment dam.

2.3 ROUTINE PROCEDURES

Routine Procedures should include the instructions, forms, and checklists that will be used to operate and maintain the dam. These materials should be prepared to guide the day-to-day operations so that nothing is overlooked and that inspections and maintenance are performed when required. This part of the M&M Plan includes the following information:

- operating instructions for spillway, outlet, and reservoir
- inspection instructions, forms, and schedules
- monitoring instructions, forms, and schedules
- maintenance instructions, forms, and schedules
- security and safety requirements

Routine Procedures do not include detailed inspection and maintenance procedures since these procedures are voluminous. Rather, they contain a guide and schedule for performing these activities. The detailed procedures for inspection and maintenance should be contained in the owner's project files. The Indiana Dam Safety Inspection

Manual contains typical details for inspections and maintenance and may be used as the basis for these procedures. Detailed procedures for reservoir operation and monitoring may be included in the M&M Plan since these procedures are generally brief and concise.

2.3.1 Operating Instructions

The M&M Plan should provide complete, clear, step-by step instructions for operating all mechanisms associated with the dam. This will typically include the outlet conduit control valve, flashboards, or possibly the spillway gates if applicable. Proper sequences should be emphasized and sketches, drawings, and photographs to aid in identifying specific handles, cranks, buttons, etc should be included. The correct method of opening and closing guard gates, gate usage during low and high flow, openings at which excessive vibrations are experienced, operating problems peculiar to a specific gate, and maximum reservoir drawdown rate should also be listed. For hydraulic and electric gates, a schematic diagram should be provided showing each component (including back-up equipment) and its place in the operating sequence.

Instructions on the general operation of the reservoir, including the regulation of inflow and outlet devices, should be given. These should state the maximum pool levels to be allowed at different times of the year, maximum and/or minimum carry over storage, and maximum and/or minimum permissible outlet releases. They should also describe operation of the outlet to limit or prevent excessive spillway flow, and the method for periodic drainage of the reservoir to permit thorough outlet or upstream slope inspection.

If periodic or ongoing releases are required for downstream water flows, irrigation, power generation, or other purposes, instructions and schedules should be included for maintaining the proper release rate. Release rates and dates should be recorded and placed in the owner’s project files.

The operating instructions should also include specific security and safety measures that are deployed at the site. This includes such things as location of fences, locks, and key-holders. It should list specific areas at the dam and around the reservoir that present a potential safety concern for site visitors and maintenance personnel, and areas where “no-trespassing” signs or “warning” signs are to be posted. Most dams and reservoirs have areas that are dangerous to visitors, such as steep slopes, areas that are slippery when wet, or areas where poisonous snakes may be present. A map or sketch showing the location of these elements may be included in the M&M Plan.

It should be noted that the typical dam in Indiana is an earth embankment dam that does not include extensive mechanical or electrical equipment. The most complicated mechanical equipment at most dams is typically an outlet drain with a control valve. This situation requires minimal operating instructions. However, safety and security provisions should be addressed at all dams, and signs should be posted at a minimum in areas where dangerous conditions may be present.

2.3.2 Inspection Instructions

A clear, step-by-step set of instructions for conducting dam safety inspections of the dam and its surroundings should also be provided. Inspection checklists (and IDNR Report Forms for high hazard dams) for recording data should be used and copies of all completed inspection records should be kept in the owner's project files. The instructions should include a list of the features to be inspected, inspection frequency and schedules, and inspection team members. The inspection team may consist of the dam owner or dam operating personnel, or it may consist of engineering consultants, depending on the type of inspection and current IDNR regulations.

Table 2-3
Inspection Recommendations

(1) **Formal Technical Inspection:** Performed initially for all dams and on a regular basis (2 to 5 yrs) thereafter.

(2) **Maintenance Inspections:** Performed on a regular basis (annual) for all dams; formal technical inspections may be conducted in place of maintenance inspections.

(3) **Informal Inspections:** Performed on an impromptu, non-scheduled basis whenever the opportunity arises, or as part of a dam monitoring program.

(4) **Special Inspections:** Performed after the occurrence of unusual or extreme events, or emergencies.

The instructions should specify the type of inspection that will be performed for the given schedules and frequency. Generally, four types of inspections will be performed: (1) formal technical inspections, (2) maintenance inspections, (3) informal inspections, and (4) special inspections.

Reporting procedures should also be spelled out, including the type and format of the report, and where the report will be placed. The report may need to be submitted to IDNR by a specific date if the dam has a high hazard classification, depending on current IDNR regulations.

Part 3 of the Indiana Dam Safety Inspection Manual provides details of inspection procedures that can be used to perform the dam inspections. It also contains a copy of a sample inspection checklist and the IDNR Report Form.

2.3.3 Monitoring Instructions

The M&M Plan should include clear instructions on how to use monitoring instruments, and when and how to take measurements at monitoring points. The purpose of each monitoring point or instrument should be stated in the instructions. A map identifying each instrument and monitoring point should also be included. Field forms for recording the data should be provided in the instructions. The monitoring points themselves, plus any seepage or other areas needing special attention should be kept clear of obscuring growth and be permanently marked, so they can be found during inspection. The monitoring points should be shown on the dam site plan discussed earlier. The help of a qualified engineer or other dam safety professional may be useful in developing this section. Subchapter 3-10, Part 2, contains more information on instrumentation and monitoring.

Monitoring can only be beneficial if the observations are recorded in an orderly way and form a clear performance record. Thus, plotting or charting of the readings will be necessary. Instructions on how to make and record each measurement or observation must be provided. If the owner's engineer is not going to plot or chart the data, instructions and forms should be developed to allow owners, operators, or maintenance personnel to do this work. An engineer or other experienced dam safety professional should be consulted for help in preparing the needed forms and with reviewing/evaluating the data and plots.

Chapter 3 (Part 2) includes typical guidelines and information for monitoring a dam.

2.3.4 Maintenance Instructions

The M&M Plan should include detailed instructions and schedules for performing periodic maintenance work at the site. This should include maintenance of the dam, the appurtenant works, and the reservoir areas. This will allow new personnel to understand the tasks and experienced personnel to make sure that they have completed the work properly.

All needed maintenance work should be identified and listed. Dam maintenance includes both routine preventive maintenance and repair of problems identified during safety inspections. Preventive maintenance includes work that is performed to maintain the dam and reservoir in good working condition and to prevent more harmful conditions from developing. This includes such tasks as mowing grass, repair of erosion rills, and removal of burrowing animals from the site. Individual maintenance tasks should be itemized on the list, with a description of the area where the maintenance is to be performed, the time it takes to complete each task, the equipment that is required, who will perform the work, the schedule for performing the tasks, and reporting procedures. Maintenance that involves the repair of problems identified during inspections should also be planned out, listing the same details as needed for preventive maintenance. Dam repairs should be scheduled based on severity of the problem, available resources, and weather conditions. For example, if a severe settlement problem is identified on the crest of the dam, it should have a high priority since further degradation could lead to

Figure 2-2 Dam needing vegetation maintenance.

dam breaching. The cause of major maintenance items, such as excessive settlement, should be identified by a qualified dam safety professional. Correcting minor rill erosion on the downstream slope could be assigned a low priority since it is not a dam safety concern. This type of repair will also be weather dependent, since grass can only be planted during specific times of the year, and the embankment should be relatively dry so that additional damage is not inflicted to the embankment slopes.

Typical routine maintenance tasks performed at most dams include the following:

- Mowing grass
- Removing brush and trees
- Removing litter and other debris
- Regrading the crest and/or access roads
- Removing burrowing animals
- Operating and lubricating gates
- Adding riprap when needed
- Sealing joints in concrete facings
- Cleaning spillway and outlet conduits
- Maintaining monitoring points
- Maintaining security of operating equipment
- Reseeding and fertilizing grass
- Testing of emergency power sources

Other maintenance that may need to be performed varies from dam to dam and is usually the result of weathering and the destructive forces encountered in the dam environment. This includes such things as repair of: embankment sloughs and slides, seepage problems, severe erosion, displaced riprap, shoreline wave erosion, embankment settlement, and concrete cracking and disintegration.

The dam owner should prepare work forms for routine items and non-routine items as well. The forms can be used to ensure the maintenance is properly completed, to track the maintenance and repairs, and to keep an up-to-date project file. The key to a successful routine maintenance program is the establishment of a schedule for performing the tasks, and compliance with that schedule.

Chapter 4 (Part 2) includes typical guidelines and information for maintaining a dam.

2.4 EMERGENCY RESPONSE PROCEDURES

Every dam owner should develop emergency response procedures as part of the M&M Plan. Emergency response procedures should consist of a clear, concise set of instructions for dealing with emergencies or potential failures at the dam.

Emergencies that threaten the safety and integrity of a dam could arise at any dam. Emergencies usually develop as a result of severe weather conditions, storms, or seismic events. However, poor dam design, construction, or maintenance may contribute to or result in an emergency. For example, a riser spillway could become clogged as a result of an improper or no trash rack, causing the reservoir level to rise and threaten the embankment stability. Or, unnoticed or uncorrected seepage problems could progress and create a potential slope stability or seepage emergency.

The amount of time that a dam owner has to react depends on the cause and severity of the emergency. If a large rainstorm is occurring and the reservoir level is rapidly rising, there may be little time to respond to the situation, and immediate action may be required. However, if a problem is relatively minor and does not pose an immediate risk to the dam stability or safety, there may be time to plan and schedule the necessary repairs (these problems are not actually emergencies, but do require attention).

In general, responses to dam problems and emergencies can be divided into three categories:

(1) **Low priority response**; implement a low priority notification procedure, and schedule and perform maintenance repairs in the near future. "Near future" depends on available resources, and the severity of the deficiency.

(2) **Medium priority response**; implement a medium priority notification procedure, and perform emergency repairs as soon as possible. "As soon as possible" is subjective, and the timing depends on the urgency of the situation.

(3) **High priority response**; implement a high priority notification procedure, and perform emergency repairs immediately. "Immediately" means now.

Table 2-5 can be used to help classify the response level required for significant dam problems and emergencies. Subchapter 2.4.3 describes procedures for the various levels of notification.

The emergency response procedures included in the M&M Plan should include the following information and procedures:

- identification of hazard area
- identification of emergency and potential risks
- notification procedures
- available resources

Table 2-4
Suggested Emergency Response Procedures

- Identify the emergency and potential risks
- Determine the response level and urgency
- Estimate the amount of time before failure may occur, if applicable
- Implement notification procedures
  - Low level notification for low priority problems
  - Medium level notification for emergency conditions
  - High level notification if failure may occur
- Mobilize equipment and resources to perform repairs
- Implement emergency repair procedures

High priority notification:
- Notify emergency coordinator, local police, fire department, and state police
- Warn residents living immediately downstream from the dam
- Notify the Indiana Department of Natural Resources
- Contact a qualified engineer for assistance
- Notify other agencies/person as deemed necessary
- Contact a repair contractor and material supply sources

Medium priority notification:
- Notify dam owner and/or emergency coordinator
- Contact IDNR and a qualified engineer for assistance
- Contact a repair contractor and material supply sources

Low priority notification:
- Notify dam owner and maintenance personnel

- emergency repair procedures

Table 2-5 Guide for Classifying Dam Response Level			
Condition or Problem	**Low Priority Response** (New or Increased Problem)	**Medium Priority Response** (Possible Failure Developing)	**High Priority Response** (Failure of Dam in Progress)
Response Urgency	Normal	Emergency	Extreme Emergency
Response Time	Near future	As soon as possible	Immediately
Notification Procedure	Low priority	Medium priority	High priority
Repair Urgency	Maintenance repairs	Emergency repairs	Emergency repairs (urgent)
Failure Status	No failure imminent	Type 1 failure (dam component failure)	Type 2 failure (uncontrolled dam breach)
Embankment Overtopping	Reservoir is rising due to blocked spillway – no storm event occurring	Reservoir is rising and is getting close to or is at emergency spillway level – no storm event is occurring	Reservoir is at or is overtopping dam causing erosion
Slides	Small, or surface slide with minor reduction of dam cross section; minor settlement; not moving or changing	Moderate slide which reduces dam cross section; no seepage or overtopping is occurring	Large slide which reduces dam cross section significantly; seepage or overtopping is occurring
Settlement	Minor settlement (<1 ft) and not progressing	Active settlement	Significant settlement; overtopping is occurring or is imminent
Cracking	Small, dry, shallow cracks in non-critical areas	Active cracks with displacement or minor seepage (clear water), or in critical areas	Significant cracking with muddy water
Backcutting of Emergency Spillway	Some erosion of spillway is progressing slowly	Erosion of spillway is progressing rapidly	Spillway has washed out, dam breaching occurred or imminent
Sinkholes	Small depressions in dam or foundation; not over critical component; not changing	Large hole over outlet, or on dam or foundation; not increasing or progressing slowly	Unstable hole over outlet, or on dam or foundation; whirlpool in reservoir
Seepage/Piping	Downstream slope is wet and soft; minor sloughing; no flowing water; no sediment in seepage or drains	Seepage is causing slides which narrows dam cross section; settlement of crest and loss of freeboard; flowing water and potential for piping	Seepage has caused large slide which has reduced freeboard to reservoir level, or dam is overtopping; piping has occurred: Sink holes in dam; whirlpool in reservoir; settlement; significant muddy water
Wave Erosion	Minor erosion, and/or minor scarping of upstream slope	Moderate and/or significant scarping of the upstream slope which is progressing towards crest	Significant erosion of crest height and/or rapidly progressing loss of upstream slope
Conduit Spillway	Minor deterioration of conduit; displaced riprap at outlet; soil adjacent to conduit outlet is wet, but no flowing water	Conduit is moderately deteriorated; flowing water adjacent to conduit and potential for piping; some settlement over conduit	Conduit is severely deteriorated; joints are leaking; piping is occurring along conduit; significant sinkholes or settlement above conduit.
Outlet Failure	Deteriorated gate or controls; rusty, scaling pipe; seepage	Cracked or perforated pipe; sediment in seepage; deeply scoured or undermined conduit; broken gate controls	Significant, muddy seepage from or adjacent to outlet; sinkholes in embankment over outlet conduit

Dam owners, operating personnel, and/or their engineers must be prepared to act promptly and effectively when a dam begins to show signs of uncontrolled breach failure. Early identification of a potential breach situation may provide additional time to warn and evacuate downstream residents and to implement measures to prevent or delay dam failure.

Because failure of a dam may take only minutes or hours to occur, it is imperative to have a detailed plan of action ready for use. However, the dam owner should use caution and must be able to make sound decisions regarding the severity of the emergency. The dam owner must assess whether the emergency condition will result in a dam component failure (Type 1) or an uncontrolled breach failure (Type 2), or whether no failure will result at all. Unnecessary evacuation of the downstream areas can be costly and detrimental to the dam owner's public image, especially if the hazard area is large and involves a large number of people and properties.

A detailed Emergency Action Plan may be prepared in lieu of emergency response procedures. The Emergency Action Plan is significantly more detailed; it is described in Part 1 of the Indiana Dam Safety Inspection Manual.

2.4.1 Identification of Hazard Area

The hazard area is the area(s) that will be affected by a dam emergency. Typically, it is the downstream area that would be affected in the event of a dam failure. However, the hazard area may also include upstream areas that may be flooded as a result of rising reservoir levels.

Figure 2-3 A large storm event can provide insight to areas of inundation in the event of a uncontrolled dam breach failure.

The dam owner should be aware of the properties and structures that could be affected if a dam failure occurs. The dam owner may be legally and financially liable for all damage that is incurred. Hazard areas may be identified using USGS Quadrangle maps, FEMA Flood Insurance Rate Maps, aerial photography and mapping, or by visual inspection of the areas adjacent the dam and reservoir. Detailed engineering studies involving dam breach analyses may also be performed to determine the hazard areas. Maps showing potential areas of flooding as a result of a dam failure are especially useful. More detailed information concerning the identification of inundation areas and the development of mapping of potential flood areas is available from the IDNR.

The estimated hazard area should be shown on a map, such as a current USGS quadrangle map. The map should be made part of the M&M Plan and kept on site in the owner's project files. Roads, buildings, dwellings, and other dams that could be affected by a dam failure should be identified on the map.

Typically, very few inundation maps are available for local officials to use in their emergency warning and evacuation plans. Consequently, local officials and dam owners will have to use available mapping and common sense in determining the potential hazard areas.

If the dam is a high hazard dam and has a large reservoir pool, evacuation of the downstream hazard area may be required if emergency repair measures are unsuccessful and dam failure is imminent. Areas nearest to the dam should be evacuated first. Flood Hazard Boundary maps can provide rough approximations of necessary evacuation areas. However, the evacuation area should be extended beyond the limits of the maximum flood area shown on these maps as floods resulting from dam failures are usually more widespread and destructive. When making these determinations, it is always better to err on the conservative side.

Whenever possible, warning of a dam failure or an impending dam failure should follow procedures already established for other emergencies in the area where the dam is located. However, it must be stressed that warning and evacuation times will be limited and that immediate evacuation must follow. Warnings delivered through personal modes such as telephones, loudspeakers, and face-to-face communications are more effective than warnings delivered impersonally, by sirens for example. Persons delivering the warnings should always say "the dam is failing," and not "flooding is expected." Warnings should be clear and concise. Residents should be advised to move to safety immediately. Police, radio and television news media should be used to the extent available and appropriate. Residents are more likely to respond if they receive warnings from several sources.

Evacuation routes and roadways should be identified. Roadblocks along potentially flooded routes may be required, and should also be identified ahead of time. Agencies and/or persons that will be required to perform emergency tasks should be identified.

The farther downstream a damage center is located, the more chance there is for a long flood warning and more time to carry out an organized evacuation. Protection of life should also be considered before anything else in an evacuation effort.

It should be noted that most dams in Indiana are not high hazard and may not require any downstream notification or evacuation.

2.4.2 Identification of Emergency and Potential Risks

Early identification of emergencies and unsafe conditions at a dam will allow prompt implementation of emergency actions and procedures. Dam owners and operators should be familiar with the principal types of failure and their telltale signs, especially if they may result in an uncontrolled breach failure. If any of the following conditions are noted, the high level emergency procedures should be implemented immediately.


Figure 2-4 Water is starting to overtop this embankment.

1. The dam is overtopping or nearly overtopping. The dam owner or operator should closely monitor the level of the reservoir during periods of heavy rainfall and runoff. If the spillway and reservoir storage capacities are exceeded, overtopping may occur. Overtopping could result if a large slide on the upstream or downstream slopes of the embankment has significantly lowered the dam crest. Blockage of pipe spillways and risers may also cause overtopping of a dam. Other conditions which could cause overtopping include significant settlement on the dam crest, sinkholes, excessive embankment soil erosion, spillway and embankment cracks, and wind-blown trees.

2. Piping (internal erosion of soil from the dam or its foundation) has developed. Piping is usually indicated by a rapid increase in seepage rate, a muddy discharge at or near the downstream toe, sinkholes on or near the embankment, and/or a whirlpool (eddy) in the reservoir. Boils at or near the downstream toe may be indications that piping is beginning. Piping may also develop along spillway and outlet conduits.

3. A large slide develops in either the upstream or downstream slope of the embankment and threatens to release the impounded water by lowering the dam crest.

4. Sudden and rapid failure of an appurtenant structure threatens complete failure of the dam and release of its impoundment.

Identification of any of these conditions at a dam should be cause for alarm and the emergency procedures should be implemented promptly. If there is any question as to the severity or urgency of the suspected problem, a qualified dam safety professional should be contacted. IDNR may also be contacted for additional advice.

The dam owner should prepare a list of critical dam features and conditions that would be checked during any emergency. For periods of unusual activity (heavy rains, earthquakes, embankment instability, etc.), the owner should record reservoir levels to determine the rate of pool rise or fall. Inspection of the embankment, downstream toe and abutments for wet areas or seepage for indications of piping through the structure or foundation is important during these events. The owner should check for abnormal sloughing of earth, depressions, and horizontal and vertical displacement of the embankment and concrete structures. If the dam is instrumented, monitoring should be performed to detect changes from normal readings that would indicate distress in the embankment. If overtopping occurs, the embankment should be closely monitored for signs of deterioration. Table 2-5 can be used to help classify dam emergencies and response levels.

After the emergency condition is identified, the potential risks associated with the condition should be evaluated. The severity of the risks will be dependent on the type of condition, reservoir level, size of reservoir, proximity of downstream property and structures, potential success of emergency repairs, etc. The risks may include release of small quantities of water from the reservoir, release of larger quantities of water, or complete dam breaching and failure. Depending on the severity of the risk to the dam, associated risks to the hazard area(s) should also be assessed. These risks may include shallow flooding of properties, extensive flooding of properties, total destruction of dwellings and other buildings, flooding of public roads, breaching of downstream dams, severe erosion, etc. The owner should determine whether the emergency will result in an uncontrolled breach failure and subsequent release of a significant quantity of water before proceeding with notification procedures.

The level of notification will depend on the severity of the emergency condition, so it is very important that the safety concerns and risks are accurately identified. Unnecessary notification should be avoided.

2.4.3 Notification Procedures

As flows over the spillway continue to increase, the owner must make a determination as to whether the embankment might be overtopped. When a determination has been made that lives and properties downstream from the dam are in serious jeopardy, notification of the appropriate agencies/persons (presented below) should be accomplished using available and predetermined communications. The dam owner should designate an “emergency coordinator(s)” that will be responsible for the coordinating all emergency activities and implementing the notification procedures. Two different notification procedures should be developed based on the type of the emergency and the hazard classification of the dam. If the emergency condition will or may result in an uncontrolled breach failure of the dam, and downstream people and structures will be affected, a **high priority notification** process should be implemented. If the emergency condition will not result in an uncontrolled breach failure of the dam, or no people or structures will be affected downstream, a **medium priority notification** process should be implemented. A third notification level, low level, is implemented for non-emergency situations where sufficient time is available to perform repairs, and the dam safety and integrity is not at immediate risk.

The response to a critical emergency situation that will or may result in an uncontrolled breach failure that will affect downstream people and structures should proceed in four steps (high priority notification). First, the owner or person who identifies the emergency should notify the emergency coordinator and/or dam owner, local law enforcement officials, and those persons residing immediately downstream from the dam. Law enforcement and local officials should then proceed with warning and evacuation procedures for potentially affected areas. Second, after notifying local law enforcement officials, the owner should contact a qualified engineer and other agencies/person (if necessary) to assist with the emergency. Third, the owner should initiate efforts to prevent or delay the failure, including contacting repair contractors and material suppliers as may be needed. Fourth, the owner or operator should notify IDNR Dam Safety personnel of the incident within 24 hours. The sequence of actions for a high priority notification is summarized below.

Owner/ Observer:

1. Notify emergency coordinator and/or owner, local officials, and warn residents living immediately downstream from the dam. Local officials include local police, fire department, and state police.
2. Contact a qualified engineer and other agencies/person as deemed necessary for additional assistance (see list below).
3. Implement actions to prevent or delay failure, including contacting repair contactor(s) and material suppliers.
4. Notify the Indiana Department of Natural Resources, Division of Water, Dams and Levees Section within 24 hours of the incident.

Local Officials:

1. Determine affected area.
2. Implement warning/evacuation plan.

If the emergency does not pose an uncontrolled breach failure or will not affect downstream people and structures, a medium priority notification process should be implemented. This process consists of the following three steps:

1. Notify dam owner and/or emergency coordinator
2. Contact a qualified engineer for assistance
3. Implement actions to prevent or delay failure, including contacting repair contactor(s) and material suppliers.
4. Notify the Indiana Department of Natural Resources, Division of Water, Dams and Levees Section within 24 hours of the incident.

The dam owner should establish a list of agencies/persons to be contacted as part of the notification process. Input for this list should be obtained from and coordinated with local law enforcement officials and county disaster assistance personnel. The following agencies/persons can offer emergency assistance in the event failure of the dam appears imminent:

1. Owner/operator (home and office)
2. Employees actively involved with dam
3. Local sheriff, police, and/or fire departments

4. State Police
5. County Disaster Services Agency
6. County Engineer
7. Indiana Department of Natural Resources, Division of Water, Dams and Levees Section
8. Local emergency management (civil defense) agencies (county and municipal)
9. Emergency Medical Services
10. Downstream residents (if practical).
11. Qualified local engineering consultants
12. Local repair contractors and material suppliers

A copy of the notification list should be posted in a prominent, readily accessible location at the dam, near a telephone and/or radio transmitter, if possible. This list should be periodically (once or twice a year) verified and updated as necessary. The list should include individual names and titles, locations, office and home telephone numbers, and radio frequencies and call signals as appropriate. Special procedures should be developed for nighttime, holiday, and weekend notification and for notification during a severe storm when telephones may not be working or highways may be impassable. The notification plan should be brief, simple, and easy to implement under any set of emergency conditions.

A primary and backup communication system which considers the possibility of a potential power blackout should be identified in the plan. Cell phones may be used in a situation like this.

A predetermined time should be established when evacuation efforts are to be terminated. Previous studies may be available to indicate at what flood level it is no longer safe to continue evacuation in each area. The time it takes for peak flood levels to reach the dam and the time needed to evacuate all people and equipment should be the determining factors in terminating evacuation assistance.

The following information should be reported when an emergency notification procedure is implemented:

1. Name of dam, lake, or reservoir, and river, stream, or tributary the dam is located on.
2. Location from highway or nearest town (U.S., state, or county road numbers); also section, township, and range, if known.
3. Nature of the problem (e.g., excessive leakage, cracks, sand boils, slides, wet spots, etc.).
4. Location of problem area in terms of embankment height, (e.g., about 1/3 up from the toe) and location along the dam's crest (e.g., 100 feet to the right of the outlet or abutment) and whether on the upstream slope, crest, or downstream slope.
5. Extent of the problem area and the amount of time until failure occurs.

6. Estimated quantity of unusual flows as well as whether the water is clear, cloudy, or muddy.
7. Water level in the reservoir below the dam's crest or below the spillway, or the gage rod reading.
8. Whether the water level in the reservoir is rising or falling.
9. Name and how to contact the person making the report.
10. Whether or not the situation appears to be worsening.
11. Whether or not the problem appears to be containable at the time of the report, or whether it is an emergency situation.
12. Current weather conditions at the site.
13. Anything else that seems important.

Figure 2-5 Backhoe being used to place an emergency pump in the reservoir.

This list should be periodically reviewed by owners' representatives who frequently visit the dam site. It will alert them to make all these observations before reporting the incident. An accurate report will allow an accurate assessment of the situation and proper implementation of the emergency response procedures.

Figure 2-6a Riser without a trash rack was clogged with the wood pallet in foreground.

A low level notification process is used when normal, low risk dam problems are found. This process consists of notifying the dam owner and maintenance personnel of the observed condition. Even though an emergency may not be present, low level problems should be identified early and scheduled for repair in the near future to prevent them from becoming worse.

2.4.4 Available Resources

Figure 2-6b The riser in figure 2-6a is visible after pallet is removed and water is drawn down.

The emergency response procedures should include a list of available resources that may be needed during a dam emergency condition. The dam owner should immediately initiate efforts to prevent or delay failure of the dam. Because of the likely limitation on time, it is important to identify in the emergency response procedures the location of available resources which may be used to attempt to avoid (delay or prevent) the failure. Any emergency repairs will require equipment, materials, labor, and expertise. For large reservoirs where failure could result in loss of life or severe damage to high value property, materials (clay, sand, gravel, stone, riprap, sandbags, cement, plastic sheeting, etc.) and equipment for handling these materials should be kept at or near the site. If this provision is not possible, then prior arrangements for use of locally available, off-site materials and equipment should be made in case of an emergency. Equipment that may be needed includes pumps, dozers, backhoes, front-end loaders, trucks, and boats. A list of local contractors and other labor sources should be prepared and kept up-to-date. Telephone numbers where these people can be contacted 24 hours per day should be included. The dam owner should contact the potential contractors ahead of time and obtain their cooperation in advance.

2.4.5 Emergency Repair Procedures

The emergency response procedures should also include potential repair procedures that may be implemented for the different types of emergencies that could threaten the dam. The most likely modes of failure were described earlier. It is important to know what types of emergency repairs should be attempted for the different modes of failure.

Owners should not allow temporary actions to become permanent repairs. This practice is dangerous because the chance of a rapid and catastrophic failure may increase if the repairs are not adequate. A qualified dam safety professional should be contacted to recommend appropriate permanent remedial measures.

Repair procedures will be dependent on the type of safety concern or emergency condition that is encountered. An emergency condition is considered to exist if either a Type 1 (component failure) or Type 2 (uncontrolled breach failure) failure has occurred or is imminent. A Type 1 failure requires a medium priority response, while a Type 2 failure requires a high priority response. Emergency repairs should be performed when either type of failure situation exists. Maintenance repairs should be performed when dam deficiencies are minor and have not progressed to an emergency status. Table 2-4 can be used to help determine if an emergency exists and the level of urgency for performing repairs.

The remainder of this chapter presents guidelines for performing emergency repairs for Type 1 (medium priority) and Type 2 (high priority) failure modes.

High priority emergency repairs (emergencies that could result in uncontrolled breach failure (Type 2).

These emergencies usually require immediate action to prevent the release of the reservoir. Therefore, it is very important that the dam owner or operator be prepared ahead of time so that a rapid response is possible. The following descriptions of possible actions to take during emergencies that could result in an uncontrolled breach are offered as guidance. These measures are preliminary and may need further development in the site specific emergency response procedures. Extreme caution should be exercised by those working around the dam during emergency conditions when there is uncontrolled flow of water.

To facilitate the procedures, repairs of impending uncontrolled breach failures are categorized by the three most common conditions a dam owner is likely to encounter: (1) embankment overtopping, (2) embankment or foundation piping, and (3) structural failure.

Embankment Overtopping

If overtopping has begun or appears imminent, the following actions may be taken:

1. Notify local authorities and other affected parties of possible failure, as applicable. Implement either a full or abbreviated notification process, depending on the situation at hand.
2. Contact a qualified dam safety professional for assistance.
3. Contact a contractor or other parties that can perform the repairs, and secure necessary repair materials.
4. Notify the Indiana Department of Natural Resources, Division of Water, Dams and Levees Section within 24 hours of the incident.
5. Be sure that the spillway(s) is not plugged with debris and is functioning as efficiently as possible. Debris removal may be difficult due to pressure from the high velocity flow and should be accomplished by using long poles or hooks. Personnel should not be allowed close to spillway inlets.
6. Open all lake drains or other gates to lower the pool level. Pumps and/or siphons may also be helpful on small reservoirs.
7. Dig a by-pass channel around the dam through an abutment. The location for this channel should be chosen with extreme caution so that the embankment will not be affected by rapid erosion of the channel. This action should not be undertaken without the supervision of a qualified dam safety professional.

Figure 2-7 Uncontrolled breach of a dam caused by component failure (piping).

8. If a bypass channel is not feasible (or in addition to a bypass channel), provide erosion resistant protection on the downstream slope where overtopping is or will occur (e.g., riprap, concrete lining, plastic sheets).
9. Create additional spillway capacity by making a controlled breach in the lowest portion of the embankment, or along the abutment. Erosion resistant materials

may need to be installed on the floor and walls of the controlled breach area.

Generally, it is not recommended to temporarily raise the top of embankments with sandbags or by other means to try to prevent overtopping during a severe storm. This action is dangerous because the flood inflow may still Increase and result in the overtopping of the raised dam. If the temporarily raised dam fails, the release of an even greater volume and depth of water would result.

Obstructions in spillways are a common cause of dam overtopping.

Embankment or Foundation Piping

If piping has developed or is imminent, the following actions may be taken:

1. Determine whether the piping can lead to an uncontrolled breach failure.
2. Contact a qualified dam safety professional for assistance.
3. Notify local authorities and other affected parties of possible failure, as applicable. Implement either a full or abbreviated notification process, depending on the situation at hand.
4. Contact a contractor or other parties that can perform the repairs, and secure necessary repair materials.
5. Notify the Indiana Department of Natural Resources, Division of Water, Dams and Levees Section within 24 hours of the incident.
6. Open all lake drains and other gates to lower the pool level. Pumps and/or siphons may also be helpful on small reservoirs.
7. Attempt to plug the "pipe" at the upstream end by dumping material into the whirlpool or sinkhole. Straw has been used effectively for this purpose. If straw is not readily available, other materials (e.g., earth, rock, Bentonite, plastic, etc.) should be tried. If the "pipe" is plugged, the owner should be aware that this is only a temporary repair. The reservoir should be fully drained, and a professional engineer should be contacted to recommend permanent remedial measures.
8. Place a protective sand and gravel filter over the exit area to hold the soil material in place and ring the filter with sandbags.

Structural Failure of Embankment or Appurtenances

If a sudden and rapid failure of an appurtenance or a large slide in the embankment has occurred or is imminent, the following actions may be taken:

1. Determine whether the slide can lead to an uncontrolled breach failure.
2. Contact a qualified dam safety professional for assistance.
3. Notify local authorities and other affected parties of possible failure, as applicable. Implement either a full or abbreviated notification process, depending on the situation at hand.
4. Contact a contractor or other parties that can perform the repairs, and secure

necessary repair materials.

5. Notify the Indiana Department of Natural Resources, Division of Water, Dams and Levees Section within 24 hours of the incident.
6. Open all lake drains and other gates to lower the pool level. Pumps and/or siphons may be helpful on small reservoirs.
7. Attempt emergency repairs to prevent or delay failure.
8. Attempt to block water movement through the dam (if occurring) by placing plastic sheets, soil, etc. on the upstream face.

Slides may be caused by seepage pressures, a saturated slope, a slope which is too steep, or possibly an earthquake. Earthquakes, although not common in Indiana, can cause structural damage to the embankment or appurtenances which might lead to complete failure of the dam. If a large slide in the upstream or downstream slope has occurred which significantly lowers the dam crest and threatens to release impounded water, sandbags can be used to temporarily raise the crest to prevent overtopping. (Temporarily raising the embankment during a severe storm is not recommended.) On large reservoirs, beaching and rapid erosion of the upstream slope by wave action could occur due to high winds. A complete breach of the dam crest may result if the slope protection fails and bare soil is exposed to wave action. A supply of large rock should be available for use during this type of emergency. Severe foundation erosion and subsequent collapse of a concrete spillway may also lower the dam crest, resulting in a potential breaching condition.

Figure 2-8 Spillway component failure that could lead to uncontrolled breach failure. Note that water is flowing from under spillway.

<u>Medium priority emergency repairs</u> (emergencies that could result, or have resulted, in component failure (Type 1).

Component failure, by definition, does not result in a significant release of water. Therefore, there is usually enough time to repair the damaged components, and in some cases, temporary repairs may be made until permanent repairs can be implemented. If the component failure is rapidly progressing, it could lead to an uncontrolled breach, and immediate repairs may be required. Temporary repair of appurtenant structures will depend on the nature of the problem. The following descriptions of possible actions to take during emergencies that have or could result in component failure are offered as guidance. These measures are preliminary and may need further development in the site specific emergency response procedures.

Loss of Freeboard or Dam Cross Section due to Wave Erosion

1. Lower water level to an elevation below the damaged area.
2. Immediately place additional riprap or sandbags in damaged areas to prevent further embankment erosion.
3. Restore freeboard with sandbags or earth fill. Place suitable-sized riprap on the damaged area to stop erosion.
4. Continue close inspection of the damaged area. Mark the damage areas with stakes and monitor on a regular, frequent basis.

Slides in the Upstream or Downstream Slope of the Embankment

1. Lower water level at a rate and to an elevation which are judged to be safe under the slide condition. If the outlet is damaged or blocked then pumping, siphoning, or a controlled breach may be required.
2. Restore lost freeboard if required. This may include placing sandbags or fill on top of the slide.
3. Stabilize slides on the downstream slope by weighing the toe area with additional soil material, rock, or gravel. If there is significant leakage, construct a sand and gravel filter over the leakage exit.
4. Monitor for additional settlement, sliding, movement, and seepage.

Flows through the Embankment, Foundation, or Abutments which Erode the Materials

1. If the entrance area of the leak in the reservoir can be found, try to plug it off with whatever materials are available such as hay bales, soil, bentonite, plastic, etc.
2. Lower the water level until the flows decrease to a non-erosive velocity or until the flow stops.
3. Place a protective sand and gravel tilter over the exit area to hold the soil materials in place.
4. Continue lowering the water level until an elevation judged to be safe is reached.
5. Continue operating at a reduced level until permanent repairs can be made.
6. Monitor and document the leakage, including leakage rate and turbidity.

Embankment Cracking

1. Lower the water level by opening the outlet (and/or pumping). Continue until the water is below the cracking.
2. Attempt to block water movement into cracks by placing plastic sheeting or soil over them.
3. Mark the extent of cracking with adequate stakes in order to monitor any increase or change in pattern. Document the observations.
4. Continue operation at a reduced level until permanent repairs can be made.

Saturation of the Embankment/Abutments

1. Lower the reservoir with the outlet works to a level determined by a qualified dam safety professional or judged to be safe.
2. Monitor the conditions frequently for leakage, piping, cracking, and slides. Document the observations.
3. Continue operation at a reduced level until permanent repairs can be made.

Settlement of Embankment

1. Determine whether the settlement is related to piping. If it is, see Embankment Piping discussed earlier.
2. Survey the existing monuments to determine the amount and rate of settlement. Install measurement points if necessary. Document the observations.
3. If the settlement is greater than one-foot, lower the reservoir with the outlet works to a level determined by a qualified dam safety professional.
4. If the settlement is not related to piping, place additional fill to restore the lost freeboard.
5. Continue operating at a reduced level until repairs can be made.

Failure of Appurtenant Structures such as the Outlet or Spillway

1. Implement temporary measures to protect the damaged structure, such as closing the outlet and providing temporary protection for the damaged spillway area. Provide temporary protection at the eroding surface by placing sandbags or riprap material.
2. Experienced professional divers may be able to quickly assess the problem and possibly implement repair.
3. Lower the water level to an elevation judged to be safe. If the outlet is inoperable, then pumping, siphoning, or a controlled breach may be required.
4. Monitor the outlet and embankment for settlement, sinkholes, and muddy leakage. Monitor leakage rate.
5. Continue operating at a low water level to prevent spillway flows.

Mass Movement of the Dam on its Foundation

1. Immediately lower water level until excessive movement stops.
2. Continue lowering water until a level judged to be safe is reached.
3. Continue operating at a reduced level until repairs can be made.

Loss of Abutment Support or Extensive Cracking in Concrete Dams

1. Lower the water level by releases through the outlet.
2. Attempt to block water movement through the dam by placing plastic sheets etc., on the upstream face.
3. Prepare to notify and evacuate downstream residents.

4. Continue lowering water to a level judged to be safe.

The following suggestions may be helpful when making a controlled breach, placing sandbags, and placing plastic sheet to control leakage.

Controlled Breach

One method of making a controlled breach is to construct a small coffer dam upstream from the breach area. Then excavate the breach through the embankment and place an appropriately sized pipe through the embankment and backfill around the pipe and re-establish the dam to embankment freeboard. The coffer dam can then be removed and water released through the newly installed pipe.

A second method also starts with the construction of a small coffer dam upstream from the breach area. The breach is then excavated one to four feet below the water level. The excavation area is lined with erosion resistant material, and the coffer dam is slowly removed. The excavated breach may be made shallower and relatively wide to help minimize exit velocities.

A third method is to line the area downstream where the breach will be made, then excavate a shallow (one foot maximum) and relatively wide breach. After the water level is lowered to the invert of the breach excavation, an additional one foot of soil is excavated. This process is repeated until the reservoir level is reduced to a safe level.

Placing Sandbags

When placing sandbags in high velocity flow water, it is difficult to keep the bags in place. In order to control water in this situation it is advisable to:

1. Make sure the bags are securely tied so the material does not wash out of them.
2. Begin placement near the shore or in a quiet area and work toward the higher velocity flow areas.

Placing Plastic Sheets

Plastic sheets normally used in construction have been employed successfully to resist erosion of a dam's downstream slope or spillway channel during storm flows. The top end of the sheet must be securely anchored in a nearly horizontal area such as the crest area, where velocities are low. Closely spaced sandbags or rocks can be used to anchor the sheet and minimize flow under the sheet. This protection should be extended beyond the dam's toe or the eroding area in the spillway by overlapping with the upper sheet over the lower one and anchoring successive sheets.

CHAPTER 3.0

DAM OPERATION

3.0 DAM OPERATION

The dam owner must possess specific knowledge about the dam and its appurtenant works to operate and maintain the dam in a safe and responsible manner. The owner must also have an understanding of the watershed area that contributes water to the reservoir, as well as impacts the reservoir may have on downstream areas. This chapter provides guidance to help the dam owner operate his/her dam more efficiently.

3.1 THE WATERSHED AND RESERVOIR LEVELS

3.1.1 The Watershed

The watershed is the upstream area of land that drains into the reservoir. The dam owner should have an understanding of the size and characteristics of the watershed, and the hydrologic cycle of water. The earth's hydrologic cycle is never-ending and is continuously at work in every watershed. During the cycle, a drop of water may be in various states and locations. Initially, water evaporates from the land surface and oceans as water vapor to become part of the atmosphere. The water vapor is transported and lifted into the atmosphere until it condenses and precipitates on the land and oceans. Precipitated water may be intercepted by vegetation, become overland flow on the ground surface, infiltrate into the ground, flow through the soil as subsurface flow, and discharge into streams and lakes as surface runoff. Large amounts of the intercepted water and surface runoff returns to the atmosphere through evaporation. Infiltrated water may percolate deeper to recharge the groundwater, and later emerge from springs or as seepage into streams, to form surface runoff. Finally, this water may flow out to the ocean or evaporate into the atmosphere. Water that infiltrates in the ground may eventually drain out of the ground into streams, rivers, and lakes within the watershed, or it may infiltrate deep into the ground and travel out of the watershed area. The precipitation that is intercepted by the vegetation, and groundwater that is taken up by the vegetation, may transpire into the atmosphere as water vapor. Thus, the hydrologic cycle is a continuous process of evaporation and precipitation.

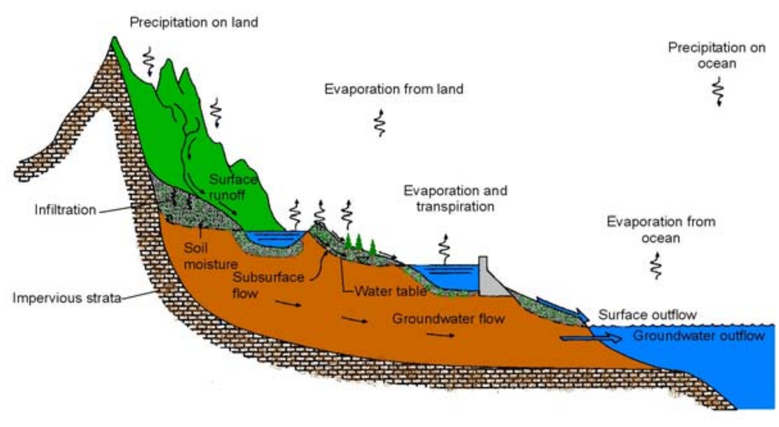

Figure 3-1 Typical watershed hydrologic cycle.

During a rain storm, it is too humid for the precipitation to evaporate or transpire by any appreciable amount; therefore, most precipitation either soaks into the ground or runs off into streams, rivers, and lakes. When it is not raining, the water that flows into the reservoir from the streams and springs is usually called the base flow, or normal flow. The base flow comes from the precipitation that infiltrated into the ground during the storm events. The base flow is typically very small compared to the flows from runoff during storm events.

The amount and rate of water that flows into a reservoir is dependent on many factors in the watershed, including the amount of precipitation, the rate at which the precipitation falls, the soil types, the land use, the topography, the size of the watershed, and distance across the watershed. Rapid flows into a reservoir can result in a dramatic rise of the water levels. High inflows are usually the result of heavy precipitation within a watershed. However, other combinations of climatic and ground conditions can cause large amounts of runoff. For example, a moderate rain on frozen ground, combined with snowmelt can produce a large amount of runoff. This is due to the fact that there would be little or no infiltration when the ground is frozen, and nearly all the rainfall would move as surface runoff.

One of the best ways for a dam owner to better understand his watershed is by compiling a history of precipitation, ground conditions, and corresponding spillway flows. Over time, the owner will become aware of the length of time between rainfall and flow increases at the dam.

3.1.2 Reservoir Levels

The normal pool level in the reservoir is the elevation of the water surface when it is not raining, and after flood flows from a storm have subsided to the base flow. For most reservoirs, it is the elevation of the principal spillway crest. The dam's storage capacity, freeboard, and spillway discharge capacity are usually based on the normal pool level. Therefore, it is important for every dam owner to know the normal pool level. The M&M Plan should include the normal pool elevation on the Dam Background Data Sheet.

The M&M Plan should also specify how and when to release water during normal and flood times, what equipment is needed, and who is responsible. It should take into account any minimum releases that may be required for downstream users, or for fishery and wildlife-habitat protection. These minimum flows should be determined in cooperation with downstream water users, and in some cases, the Indiana Department of Natural Resources.

The owner should consider the riparian rights of downstream property owners when releasing or impounding water.

Reservoir levels needed to protect upstream users should also be specified in the M&M Plan, if required. This may require that minimum, normal, and maximum water levels be established. If the reservoir level is raised, flowage rights or easements must be checked. The design storm event for maximum water level determination may be stipulated by a local or state agency, so the dam owner must be familiar with all applicable regulations. For a properly designed dam and reservoir area, all significant structures should be placed above maximum water levels.

Figure 3-2 A slope stability issue required drawdown of this reservoir until improvements were made (siphons used).

Reservoir pool levels are often controlled by spillway gates, lake drain and release structures, and flashboards. A general rule of thumb for safety is that pool level drawdown rates should not exceed 1 foot per day, except during emergency situations. Relatively flat slopes or slopes with free draining upstream zones can withstand more rapid drawdown rates, up to a maximum of 6 inches per day. Rapid drawdown of the pool may leave the upstream slope saturated and without support, and could result in sloughs and slides. If there is any question about the allowable drawdown rate, a qualified dam safety professional should be contacted. Listed below are conditions or instances that could require the pool level to be permanently or temporarily adjusted:

- A problem develops that requires the permanent pool to be lowered. Drawdown is temporary until the problem is solved.
- Water is released at a controlled rate to the downstream channel to supplement streamflow during dry conditions. This action may temporarily lower the reservoir level.
- Water-supply reservoir levels will fluctuate according to the service area's demand for water and inflow rates. Flashboards are sometimes used to permanently or temporarily raise the pool level of water-supply reservoirs. Flashboards should not be installed or allowed unless there is sufficient freeboard remaining to safely pass the design flood.
- The reservoir level is drawn down to facilitate repair of boat docks, to retard growth of aquatic vegetation along the shoreline, or to provide additional storage for spring runoff.
- Pool levels are sometimes adjusted for recreation, hydropower, or waterfowl and fish management.

3.2 OUTLETS AND DRAINS

The reservoir drain, or outlet, should always be operable so that the pool level can be drawn down in case of an emergency or for necessary repairs to the dam. Drain valves or gates that have not been operated for a long time may get stuck from corrosion, or blocked with sediment or other debris. On the other hand, if the valve cannot be closed after it is opened, the impoundment could be completely drained. An uncontrolled and rapid drawdown could also induce more serious problems such as downstream flooding and erosion, or slides in the saturated upstream slope of the embankment. Therefore, before operating a valve or gate, it should be inspected and all appropriate parts lubricated and repaired. It may also be prudent to advise downstream residents of large or prolonged discharges.

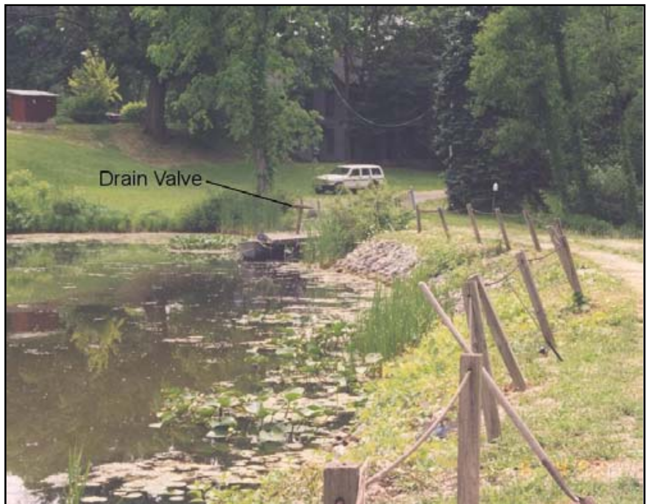

Figure 3-3a Outlet valve located under pier (not recommended) built over the riser. Figure 3.3b shows close-up of valve stem.

To test a valve or gate without lowering the lake, the drain inlet upstream from the valve must be physically blocked. Some drain structures have been designed with this capability and have dual valves or gates, or slots for stoplogs (sometimes called bulkheads) located upstream of the drain valve. Divers can be hired to inspect the drain inlet and may be able to construct a temporary block at the inlet for testing purposes.


Figure 3-3b Make-shift valve stem handle.

Other problems may be encountered when operating the reservoir drain. Sediment can build up and block the drain inlet. Debris can be carried into the valve chamber, thereby hindering its function if an effective trash rack is not present. The potential that these problems will occur is greatly reduced if the valve or gate is operated and maintained periodically. The gate or valve controlling the drain should be operated from the fully closed to fully open position at least twice a year. It is preferable that the drain be operated four times a year. Early detection of equipment problems or breakdowns and confidence in equipment operability are benefits of routine inspection and operation. Figure 3-3a shows a make-shift pier constructed over the principal spillway riser pipe with the valve actuator projecting above the pier. Figure 3-3b shows a close-up view of the valve actuator; a hole was left in the pier for inflows to the riser (this practice is not recommended).

The best location for drain valves is upstream from the centerline of the dam. Older dams often have drains with valves at the downstream end. This design results in the entire conduit being under the constant pressure of the reservoir when the valve is closed. If a leak should develop in that portion of the conduit within the embankment, saturation, erosion, and possibly failure of the embankment could occur in a short period of time. A depression in the soil surface over the pipe may be a sign that soil is being removed from around the pipe. Older structures that utilize the downstream valve design should be monitored closely and owners should plan to relocate the valve upstream or install a new drain structure. Inspectors should closely examine the drain outlet for signs of possible problems.

All reservoirs should have provisions or a plan for water level drawdown during emergencies. Permanent drawdown devices incorporated in the embankment at the time of construction are preferable. Dams that have no drawdown facilities may be retrofitted with siphons for reservoir drawdown. As a last resort, or as a supplement to existing drawdown equipment, standby pumps may be kept near the dam for drawdown. If a pump is used, electrical or fuel supplies must be maintained around the clock.

Figure 3-4 Stem for drawdown control valve located in riser box.

3.3 MECHANICAL EQUIPMENT

Mechanical equipment typically includes spillway gates, sluice gates or valves for reservoir drains or water supply pipes, stoplogs, sump pumps, flashboards, relief wells, emergency power sources, siphons, and other devices. All mechanical and associated electrical equipment should be operated at least once a year, and more often if the equipment systems are complex. The annual test should be conducted through the full operating range under actual operating conditions to determine that the equipment performs satisfactorily. Operating instructions should be checked for clarity and maintained in a secure, but readily accessible location. Each operating device should be permanently marked for easy identification. All operating equipment should be accessible, and equipment controls should be checked for proper security to prevent vandalism.

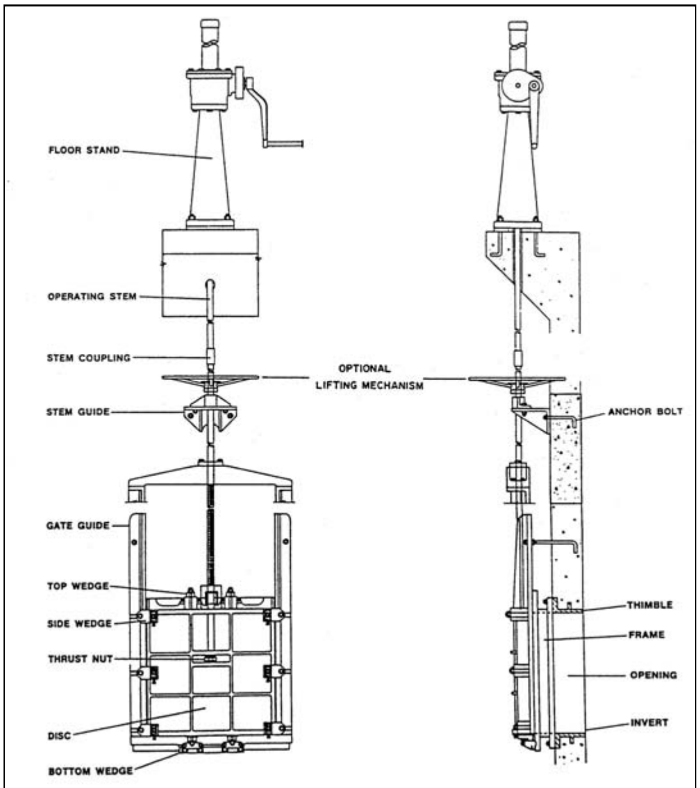

Figure 3-5 Schematic of sluice gate valve.

Many dams have no mechanical or electrical equipment, while some have only mechanical reservoir drain equipment. Earth embankment dams in Indiana typically have no mechanical or electrical equipment, or have an outlet control valve only.

Figure 3-6 Large gates with complex mechanical and electrical equipment.

For dams with mechanical and electrical equipment, all equipment should be checked for proper lubrication, smooth operation, vibration, unusual noises, and overheating. The adequacy and reliability of the power supply should also be checked during operation of the equipment. Auxiliary power sources and remote control systems should be tested for adequate and reliable operation at least monthly. All equipment should be examined for any damaged, deteriorated, corroded, cavitated, loose, worn, or broken parts. Gate stems and couplings should be examined for corrosion, broken or worn parts, and damage to protective coatings. Fluidways, leaves, metal seats, guides, and seals of gates and valves should be examined for damage due to cavitation, wear, misalignment, corrosion, and leakage. Sump pumps should be examined and operated to verify reliability and satisfactory performance. Air vents for pipes, gates and valves should be checked to confirm that they are open and protected. Wire rope or chain connections at gates should be examined for proper lubrication, and worn or broken parts. Rubber or neoprene gate seals should be examined for deterioration, cracking, wear, and leakage. Hydraulic hoists and controls should be operated and checked for oil leaks and wear. Hoist piston and indicator stems should be examined for contamination and for rough areas that could damage packings. All fasteners (bolts and nuts) should be checked to make sure that they are tight; if there is any vibration in the system, chances are that the fasteners will become loose.


Figure 3-7 Stoplogs in spillway.

Many dams have structures above and below ground that require some type of access. Water supply outlet works, reservoir drains, gated spillways, drop inlet spillways, and toe drain manhole interceptors are typical structures that will require bridges, ladders, or walkways. Care should be taken to properly design, install, and maintain these means of access for the safety of persons using them. State and local codes on safety should be followed. Requirements for walkways may include toe plates and handrails. Fixed ladders should have proper rung spacing and safety climbing devices, if necessary. Access ladders, walkways, and handrails should be examined for deteriorated or broken parts or other unsafe conditions. All equipment should be routinely checked and operated as applicable to ensure that it is in good working condition.

Stoplogs, bulkhead gates, and lifting frames or beams should be examined to determine their availability and condition. The availability and locations of equipment for moving, lifting, and placing stoplogs, bulkheads, and trash racks should also be verified. Stoplogs and bulkhead gates may require periodic installation/removal to verify that they can be installed in an emergency.

Flashboards are usually wood boards installed in an upright position along the crest of the spillway to raise the normal pool level. Flashboards should not be installed or allowed unless professional investigation indicates there is sufficient freeboard remaining to safely pass the design flood. Some flash board installations are designed to fail when subjected to a certain depth of flowing water, thereby recovering the original spillway capacity. However, flashboards designed to fail may not be reliable and are not recommended. The support structure for the flashboards should be examined for damage due to wear, misalignment, corrosion, and leakage, and repaired as necessary. The flashboards should be removed periodically (at least once a year) as a check for freedom of movement.

3.4 WINTERIZING TECHNIQUES

Ice can pose problems at spillways and around other structures in reservoirs during the winter months. Ice formation can be prevented by heaters, aeration equipment, or forced movement of water. Ice in conduit outlets or stilling basins can impair their proper functioning, or reduce their discharge capacity. The owner should be aware of these potential problems and take appropriate action during extended periods of severe cold weather if ice will be a problem. Ice damage from impact can also occur during the spring thaw when large chunks of ice begin to break free and strike concrete or metal structures.

Other winterizing activities may include:

(1) Seeding bare areas so that vegetation is established before onset of winter.
(2) Removing flashboards for storage.
(3) Opening valves slightly to provide a small flow to prevent freezing.

The pool level of a reservoir may be lowered for the winter months to facilitate repair of boat docks and other structures, to retard growth of aquatic vegetation, to provide additional spring flood storage, or to prevent ice damage.

3.5 SEDIMENTATION AND DREDGING

Figure 3-8 Typical dredging operation to remove sediment from a reservoir.

Erosion and sedimentation are natural processes in which soil particles are detached from the earth by raindrops or flowing water and carried by stream flow. Stream velocity, among other factors, determines the capacity of streams to transport sediments. When streams enter lakes, their velocities suddenly drop and the sediment load is deposited on the lake bottom.

Sedimentation occurs in every reservoir, regardless of whether the lake is natural or created by a dam. Sedimentation rates vary widely and depend on many watershed factors. Among these are soil type, land cover, land slope, land use, stream slope, size of watershed, total annual precipitation, number and intensity of severe storm events, material in the streambed, and volume of the reservoir with respect to size of the drainage area. Typically, most of the sediment enters lakes and reservoirs during a few large flood events that occur each year. Sediment deposits first become apparent when deltas build up at the mouths of streams entering the lake. Aquatic vegetation, such as cattails and lily pads, soon develop in the shallow water over these deltas. As sediment deposition continues, the delta will rise above the water surface. Sedimentation can reduce the flood storage capacity of the reservoir, however, sediment removal by dredging may be prohibitively expensive. Therefore, the best practice is to control the sediment within the watershed to keep it out of the reservoir. The best practices to control sedimentation in the watershed area can be found in the "Indiana Drainage Handbook" and the "Indiana Handbook for Drainage Control in Developing Areas."

For ponds with smaller drainage areas, vegetated strips around the pond will act as filters and trap much of the sediment. These are especially effective for ponds where much of the runoff enters as sheet flow rather than flow from small streams.

3.6 SITE ACCESS

Figure 3-9 Public road on dam crest.

The safe operation of a dam depends on reliable and safe means of access. Usually this involves maintaining a road to the dam. The road should have an all--weather surface and be suitable for the passage of automobiles and any required equipment for servicing the dam. Cut-and-fill slopes uphill and downhill from the road should be stable under all conditions. The road surface should be located above the projected high-water elevations of any adjacent streams and the reservoir pool so access can be maintained at times of flooding.

3.7 VANDALISM

Vandalism is a common problem for all dam owners. Particularly susceptible to damage are the vegetated surfaces of the embankment, mechanical equipment, manhole covers, and rock riprap. Every precaution should be taken to limit access to the dam by unauthorized persons and vehicles. "No trespassing signs" are commonly used to restrict access.

Dirt bikes (motorcycles), off-road-vehicles, and four-wheel drive vehicles can severely damage the vegetation on embankments. Worn areas can lead to erosion and more serious problems. Constructed barriers such as fences, gates, and cables strung between poles are effective ways to limit access of these vehicles to the dam. A highway metal guardrail constructed immediately adjacent to the toe of the downstream slope is an excellent means for keeping vehicles off embankments. However, this may interfere with the operation of mowing equipment.

Figure 3-10 "No Trespassing" signs can help deter vandalism and damage to embankments.

Fishing from embankments can also create problems. Fishermen will often build fires which can kill adjacent vegetation. Fishermen also create paths and may tend to kill the vegetation in areas of repeated use.

Mechanical equipment and its associated control mechanisms should be protected. Buildings containing mechanical equipment should be sturdy, have protected windows and heavy-duty doors, and should be secured with dead bolt locks or padlocks. Detachable controls such as handles and wheels should be removed when not in use and stored inside. Other controls should be secured with locks and heavy chains, where possible. Manhole covers are subject to removal and are often thrown into the lake or spillway by vandals.

Rock used as riprap around dams is occasionally thrown into the lake, spillways, stilling basins, pipe spillway risers, and elsewhere. Riprap is sometimes moved by fishermen to form benches. The best way to prevent this abuse is to use rock too large and heavy to move easily or to slush grout the riprap. Otherwise, the rock must be constantly replenished and other damages repaired.

3.8 PUBLIC SAFETY

Owners should be aware of their responsibility for public safety, including the safety of people not authorized to use the facility. "No Trespassing" signs should be posted and fences and warning signs should be erected around dangerous areas.


Figure 3-11 Outfalls from low head dams are dangerous.

Owners of low-head dams should be aware that these dams are potentially dangerous to boaters and canoeists. During high flow conditions the dam may appear as only a "bump" or ripple in the water surface. This tranquil scene is very deceptive and does not indicate the dangerous conditions that may exist. If a canoe safely negotiates the "bump", backflow just downstream from the dam can act to pull the canoe into the dam and overturn it. The hydraulic action of water passing over the dam creates a "roller" that can trap the victims, continuously pulling them beneath the surface and preventing them from swimming downstream or to the banks. Extremely large riprap (stones weighing 2 to 4 tons each) placed immediately downstream from low-head dams has been effective in breaking up the "roller." A hydraulic engineer should be contacted to properly design any similar corrective measures. Warning buoys, signs, or cable with warning signs stretched across the stream can be effective in discouraging canoeists, but these are often ignored and are difficult to maintain.

3.9 DESIGN MODIFICATIONS


Figure 3-12 This building, constructed in the emergency spillway, reduces discharge capacity.

Alteration of a dam or spillway without adequate engineering design and supervision could result in the spillway or dam being Inadequate in capacity or function. This could lead to a costly repair or complete failure of the structure. In addition, approval by the IDNR of any proposed changes may be required by current state law.

One of the more common errors made by dam owners is raising the normal pool elevation by permanently elevating the crest of the principal spillway. This action not only results in a decrease in storage available during a flood event but also reduces the capacity of the spillway by reducing the hydraulic head (total depth available to "push" water through the spillway). Raising the normal pool will usually cause the emergency spillway to flow more frequently than its design allows, thus increasing its maintenance cost.

Emergency spillways are typically designed to engage only for floods equaling or exceeding the 100-year event. Because the spillway flows so infrequently, owners are tempted to find other uses for it. Temporary uses such as parking or boat launching are acceptable. Permanent alteration of the spillway shape or construction of a building or other structure in the spillway could seriously affect the spillway's ability to function properly and should not be undertaken.

3.10 INSTRUMENTATION AND MONITORING

3.10.1 Overview

Instrumentation refers to the method and equipment used to make physical measurements of dams. The equipment may consist of sophisticated instruments such as permanently installed strain gages for measuring foundation or embankment movements, or may be as simple as a bucket and stopwatch for quick estimates of seepage flows. Monitoring refers to gathering and assimilating data from the instrumentation and evaluating the results. Instrumentation is not a substitute for inspection; it is a supplement to the visual observations made during an inspection. Visual observations combined with instrumentation data provide the basis for assessing embankment and foundation performance and safety during operation of the reservoir. The amount and type of instrumentation used at a dam depends on the type of dam and the conditions encountered. Most dams in Indiana do not have any instrumentation inplace, however, as described below, it is recommended that all dams have a minimum set of measurement capability.

Instrumentation of a dam can provide data to determine if the completed structure is functioning as intended and to provide a continuing surveillance of the structure to warn of any developments, or changes which endanger its safety.

A dam or its appurtenant works will normally experience changes throughout their life. The changes which occur and the factors causing the changes may be identified through the use of instrumentation. Furthermore, instrumentation can make it possible to distinguish between normal and abnormal changes. Knowledge of the changes which occur can enable the dam owner to make intelligent decisions regarding maintenance and repairs. The changes which occur generally include: (1) vertical displacement (settlement); (2) horizontal displacement (change in alignment); (3) internal wetting or saturation of the embankment, and (4) various forms of deterioration (cracking, erosion, weathering, etc.).

Knowing that changes occur is helpful, but more important is understanding the cause. The first changes the dam experiences usually occur during construction. As the height of the dam is increased, the material in the lower portion of the dam is compressed due to the weight of the material on top. The foundation may also compress (settle) due to the weight of the embankment or dam. The changes which occur during construction may not be limited to settlement. For example, instrumentation of earth dams under construction has shown that horizontal displacement (spreading) occurs as well. The first filling of the reservoir will create a new imbalance of forces which may cause more horizontal displacement and additional settlement as the wetting of the embankment progresses. Other factors which cause continual changes are variations in: (1) the depth of stored water; (2) the length of time maximum storage depth is present; (3) seismic activity; (4) seepage of water though or under the dam; (5) adverse weather conditions; and (6) the rate that the reservoir may be drawn down.

A dam instrumentation program must be properly designed and consistent with other project components, must be based on prevailing geotechnical conditions at the dam, and must include consideration of the hydrologic and hydraulic factors present both before and after the project is in operation. The timetable for taking measurements must be established in advance and adhered to, and the methods of data analysis must be appropriate for the type of instruments and conditions being monitored. An instrumentation program should involve instruments and evaluation methods that are as simple and straightforward as the project will allow. The equipment and methods available to monitor conditions that can lead to dam failure include a wide spectrum of instruments and procedures ranging from very simple to very complex. Instruments designed for monitoring potential deficiencies at existing dams must take into account the threat to life and property that the dam presents. Thus, the extent and nature of the instrumentation depends not only on the complexity of the dam and the size of the reservoir, but also on the potential for loss of life and property downstream of the dam. The knowledge and experience of the personnel involved in the design, installation, monitoring, and evaluation of an instrumentation system is of prime importance to the success of the program.

Careful monitoring can prevent costly problems, however sloppy measuring techniques or practices and poorly maintained instrumentation can hide a problem or create a false alarm. Therefore, the owner must have a consistent and systematic approach to monitoring of the dam. Also, by having concise records of the measurements, the owner can quickly determine if a problem is developing. The owner should fully understand the purpose of each instrument in order to understand the use of recorded measurements.

Collecting the data from instrumentation is the first step in a monitoring program. After the data is gathered, it should be reviewed and analyzed by a qualified dam safety professional knowledgeable in dam/foundation responses.

3.10.2 Objectives of Instrumentation and Monitoring

There are four principal objectives for instrumentation and monitoring of dams:

1. Warning of a Problem - Often, instruments can detect unusual changes, such as fluctuations in water pressure, and internal embankment movements that are not visible. In other cases, gradual progressive changes in seepage flow, which would go unnoticed visually, can be monitored regularly. Monitoring can warn of the development of a serious seepage problem. Instrumentation data is often used to predict future behavior of the dam based on current conditions.

2. Analyzing and Defining a Problem - Instrumentation data is frequently used to provide engineering information necessary for analyzing and defining the extent of a problem. For example, downstream movement of a dam because of high reservoir water pressure may be analyzed to determine if the movement is uniformly distributed along the dam, whether the movement is in the dam, the foundation, or both, and whether the movement is continuing at a constant, increasing, or decreasing rate. Such information can then be used to design corrective measures. Cracks can be measured and monitored to determine if they are remaining constant or getting worse. Seepage rates can be measured and monitored with time and with fluctuations in reservoir level. Instrumentation can be very valuable in the determination of the specific cause or causes of problems and failures.

3. Verification of Satisfactory Performance - Instruments may be installed to verify that the dam is performing as expected, to verify the design parameters and assumptions, or to verify construction techniques. Instruments installed at a dam may infrequently (or even never) show any anomaly or problem. However, even this information is valuable because it shows that the dam is performing as designed and provides peace of mind to an owner. In some cases a problem may appear to be occurring or imminent, but instrument readings might show that the deficiency (e.g., increased seepage) is normal and was foreseen in the dam's design (i.e., a result of higher than normal reservoir level).

Table 3-1
Dam Instrumentation Equipment Categorized by Function

1. Deformation
- Hand measuring tools
- Surveying methods
- Probe Extensometers
- Fixed embankment extensometers
- Subsurface settlement points
- Fixed borehole extensometers
- Inclinometers
- Tiltmeter
- Liquid level gages

2. Groundwater pressure
- Open standpipe piezometer
- Twin-tube hydraulic piezometer
- Pneumatic piezometer
- Vibrating wire piezometer
- Electrical wire piezometer
- Pressure cells

3. Water level
- Observation well
- Piezometers
- Water level sensor

4. Seepage flow
- Weirs
- Parshall flumes
- Catch containers and timer
- Velocity meter

5. Water quality
- Laboratory analysis
- Sample jars and visual inspection
- Turbidimeter
- Turbidity sensor

6. Temperature
- Thermistor
- Thermocouple
- Resistance temperature devices
- Density thermometer

7. Cracks and joints
- Hand measuring tools
- Surveying methods
- Joint meter
- Portable crack measuring microscope
- Dial gage
- Mechanical scratch gage
- Crack comparator

8. Seismic activity
- Accelerometer
- Peak acceleration recorders

9. Weather and precipitation
- Precipitation gage
- Wind gage

10. Stress and strain
- Electrical Resistance strain gage
- Vibrating wire
- Hydraulic load cell
- Embeddable strain gage
- Stress gage and meter
- Strain gage and meter

Instrumentation may also be installed to verify that the dam was constructed properly; poor construction practices may result in adverse behavior that can be detected with instrumentation.

4. Evaluating Remedial Action Performance - Many dams, particularly older dams, are modified to allow for increased capacity or to correct a deficiency. Instrument readings taken before and after the change may allow analysis and evaluation of the performance of the modification. The data can be used to determine the effectiveness of the modifications or improvements and the effect of the change(s) on existing conditions.

Instrumentation may also be valuable for providing data for potential litigation relative to construction claims, damage claims from adjacent property owners arising from adverse events, or claims relative to changed water conditions downstream or adjacent to a dam. In some cases, data from instrumentation may be used to develop design criteria and construction techniques for new dams. These reasons for instrumentation may be important when applicable, but they are not considered to be principal objectives.

The types of instrumentation available can be categorized by the conditions that are typically assessed at dams (see Table 3-1). The ten most commonly monitored conditions include the following:

(1) deformation or movements
(2) groundwater pressure
(3) water level
(4) seepage flow
(5) water quality
(6) temperature
(7) cracks and joints
(8) seismic activity
(9) weather and precipitation
(10) stress and strain

Conditions not on the list, such as concrete deterioration, soil erosion, and inadequate vegetation can be monitored with simple instruments, including hand measuring tools and a camera.

3.10.3 Types of Instrumentation

Most of the instrumentation that is used to monitor dam performance is complicated and requires qualified personnel to install and use the equipment. This is especially true for the various instruments available for monitoring concrete structures. Many instruments can be automated and connected to continuous data loggers to simplify data collection. This manual does not provide detailed information for all of the instrumentation that is available, but rather, it focuses on some of the more common, simpler equipment that a typical dam owner is likely to use. Table 3-1 summarizes the types of instruments that are available, categorized by the ten most commonly monitored conditions at dams.

Due to the expense, the use of sophisticated and extensive instrumentation to ensure safety is usually limited to large dams where failure would result in loss of life and a great deal of damage. A full-scale instrumentation and monitoring program requires professional design. The type of instruments and monitoring program that may be deployed depends on the type of conditions encountered and the type of structure being investigated. A brief description of some of the more complex equipment is provided herein to give the dam owner a basic understanding of the principles of these instruments.

Monitoring by private dam owners in Indiana is usually limited to visual observation. It is very important that the observations are accurate, made on a routine schedule, and recorded. An inspection checklist should be used for visual inspections. Owners are encouraged to use photographs with identifying dates and labels as a permanent record to be filed with other dam records.

Simple Monitoring Devices

The following devices are relatively inexpensive and can easily be used by most dam owners to monitor dams.

Camera - Photographs which have been dated and labeled provide an excellent record of existing conditions, and if taken periodically from the same location, can be used for comparison. Photographs should be taken during all inspections to supplement written and visual observations. They are valuable in documenting the location and severity of wet areas, erosion, and concrete deterioration.

Yardstick or folding rule - This portable monitoring device is not only inexpensive but has a number of uses. It can be used to measure cracks, scarps, erosion gullies, settlement, trees, wet areas, and slab or wall movement. Records should be kept of all observations for comparative purposes.

Bucket and Watch - Flow rates in gallons per minute for small weirs, seeps, and pipe outlets can be measured by timing how long it takes to fill a bucket (or other container) of known capacity.

Weirs - The V-notch weir is probably the most commonly used device to measure flow rates of seepage. Effective readings must be taken periodically under similar influences, such as reservoir level and local runoff conditions. Many times after installation, the weirs are neglected and a few good readings become useless for lack of comparative data. Consequently, the V-notch weir must be maintained.

Flumes - For larger flows, the Parshall flume is preferred to larger V-notch weirs because the flume will not restrict the flow as much as the weir. Parshall flumes can be purchased through a supplier of scientific equipment.

Piezometers - Piezometers are instruments used to measure the water pressure in the embankment and foundation soil pores and are installed at various levels in a drill hole. Readings are usually taken by measuring the elevation of water in a standpipe. Seepage pressure can be determined from piezometer readings. Water levels can easily be measured with the use of a portable, battery-operated water-level probe and meter. The probe is lowered into the well or piezometer by means of the electrical cable; when the tip of the probe is submersed, the electrical circuit in the probe is closed and the hand-held meter indicates the presence of water. A water level sensor that measures water pressure can also be used in piezometers to measure water level.

Survey monuments - Survey monuments are usually installed along the crest of the dam to check its vertical and horizontal alignments (with known reference points and elevations). Measurements of these monuments must be precise and are obtained using surveying instruments.

Observations Wells - Observation wells can be installed in the embankment or foundation and are used to determine the ground-water level. The same type of probes used in piezometers can be used in observation wells.

Inclinometers - Inclinometers are instruments that are lowered into a vertical casing and are used to measure horizontal deflection. Inclinometers are often used to determine the rate of movement of a slide. They are usually used to measure internal displacements within earth embankments of higher dams.

Piezometers, settlement monuments, observation wells, and inclinometers are often found on large dams and are described briefly herein. The installation and monitoring of these devices usually requires professional assistance.

Electronic Instrumentation

Most electronic instrumentation consists of three components: a transducer, a data acquisition system, and a linkage between these two components. A transducer is a component that converts a physical change (pressure or movement) into a corresponding electrical output signal. Data acquisition systems range from simple portable readout units to complex automatic systems. Most instruments fall into one of five categories based on the method of operation. A brief, technical description of each category of equipment is provided below.

(1) pneumatic devices
(2) vibrating wire devices
(3) electrical resistance strain gage devices
(4) electrical transducers for measuring linear displacement
(5) other electrical systems

Pneumatic devices

Pneumatic devices measure pressures in the soil with the use of a controlled gas supply. They are typically used for pneumatic piezometers, earth pressure cells, and liquid level settlement gages. The pressure within the soil that is in contact with the instrument probe is the pressure of interest. An increasing gas pressure is applied to the inlet tube of the probe; while the gas pressure in the tube is less than that in the soil, it merely builds up in the inlet tube. When the gas pressure in the tube exceeds the pressure in the soil, a diaphragm in the probe deflects, allowing gas to circulate behind the diaphragm into the outlet tube while the gas flow is sensed using a gas flow detector. The gas supply is then shut off at the inlet valve, and any pressure in the tube that is greater than the soil pressure bleeds away, allowing the diaphragm to return to its original position. When this happens, the pressure in the inlet tube equals the pressure in the soil. This pressure is read on a Bourdon tube or electrical pressure gage. Many detailed issues need to be considered when selecting a pneumatic device, including the sensitivity of the reading to diaphragm displacement, gas flow, tubing length and diameter, type of tubing, tubing fittings, gas, and pressure gage.

Vibrating wire devices

Vibrating wire devices are used in pressure sensors for piezometers, earth pressure cells, liquid level settlement gages, and in numerous deformation gages. In a vibrating wire device, a length of steel wire is clamped at its ends and tensioned so that it is free to vibrate at its natural frequency. As with a piano string, the frequency of vibration of the wire varies with the wire tension. Thus, with small relative movements between the two end clamps of the vibrating wire device, the frequency of the vibration of the wire varies. The movements are caused by pressure being exerted against the end clamps, such as water pressure or earth pressure. The wire can therefore be used as a pressure sensor by measuring the frequency of vibration. The wire is plucked magnetically by an electrical coil attached near the wire at its midpoint, and either this same coil or a second coil is used to measure the period or frequency of vibration. The frequency is proportional to the pressure being applied on the end clamps. Detailed issues that need to be considered when selecting a vibrating wire device include the method of clamping the wire, preventing corrosion or seepage, and pre-treating the transducer to prevent significant zero drift. The attached wire is under near maximum tension at zero pressure. This tension applies the greatest demand on the clamping and annealing of wire, a condition that may cause creeping and slippage of the wire at the clamps, which results in a frequency reduction unrelated to strain. This is commonly known as drift of the baseline pressure or zero drift. With vibrating wire transducers undesirable effects involving signal cable resistance, contact resistance, electrical signal seepage to ground, or length of signal cable are negligible. Very long cable lengths are acceptable.

Electrical resistance strain gage devices

Electrical resistance strain gages are very common and are used in many measurement devices, including strain gages, joint meters, and pressure cells. An electrical resistance strain gage is a conductor with the basic property that resistance changes in direct proportion to change in length. The relationship between resistance change and length change is given by the gage factor. Output from the gages is normally measured using a Wheatstone bridge circuit. Electrical resistance strain gages can be packaged as bonded wire, unbonded wire, bonded foil, and weldable gages. The measured resistance change can be strongly influenced by signal cable length, contact, moisture, temperature, and leakage to ground. However, correction for these influences can be made by measuring the resistance of the various system components (cable, contact, etc.) and subtracting the resistance from the total resistance. Various companies now manufacture low-current signal transducers (4- to 20-milliamp range) that are unaffected by resistance problems.

Electrical transducers for measuring linear displacement

A linear variable differential transformer (LVDT) consists of a movable magnetic core passing through one primary and two secondary coils. An AC voltage is applied to the primary coil, thereby inducing an AC voltage in each secondary coil, with a magnitude that depends on the proximity of the magnetic core to each secondary coil. Changes in pressure or movement are measured as the core-to-coil distance changes proportional to the changes.

A direct current differential transformer (DCDT) is similar to a LVDT, except that unwanted cable effects associated with LVDT's are avoided by using DC voltages, requiring miniaturizing the electrical circuitry and placing additional components within the transducer housing.

A linear potentiometer is a device with a movable slider, usually called a wiper that makes electrical contact along a fixed resistance strip. A regulated DC voltage is applied to the two ends of the resistance strip and the voltage or resistance between the one end of the strip and the wiper is measured as the output signal. The voltage between the end of the strip and the wiper varies as the wiper moves from one end of the strip to the other.

Other electrical systems

Force balance accelerometers are used as tilt sensors in inclinometers. The device consists of a mass suspended in the magnetic field of a position detector. When the mass is subjected to a gravity force along its sensitive axis, it tries to move, and the motion induces a current change in the position detector. This current change is fed back through a servo-amplifier to a restoring coil, which imparts an electromagnetic force to the mass that is equal and opposite of the initiating gravity force. The mass is thus held in balance and does not move. The current through the restoring coil is measured by the voltage across a precision resistor. This voltage is directly proportional to the input force.

The magnet/reed switch system is used in probe extensometers. It is an on/off position detector, arranged to indicate when the reed switch is in a certain position with respect to a ring magnet. The switch contacts are normally open and one of the reeds must be magnetically susceptible. When the switch enters a sufficiently strong magnetic field, the reed contacts snap closed and remain closed as long as they stay in the magnetic field. The closed contacts actuate a buzzer or indicator light in a portable readout unit.

Induction coil transducers are also used in probe extensometers. An electrical coil is powered to create a magnetic field around the coil. When this coil is placed inside a steel wire ring (with no external electrical connection), a voltage is induced in the ring, which in turn alters the current in the coil because its inductance changes. The current in the coil is a maximum when the coil is centered inside the ring; thus, by measuring current in the coil, the transducer can be used as a proximity sensor.
Sonic transducers can be used to monitor water level in open standpipe piezometers and weir stilling basins. The transducer is mounted above the water surface. Sound pulses travel to the water surface and are reflected back to the transducer. The distance to the water surface is determined from the measured pulse time and the known velocity of sound waves, corrected for errors induced by temperature change.

Resistance temperature devices depend on the principle that change in electrical resistance of a wire is proportional to temperature change. The wire is usually mounted on a postage-stamp-sized backing or wound on a small-diameter coil.

3.10.4 Instrumentation Usage

Instrumentation usage depends on the type of dam and the conditions encountered. A determination of the number, type, and location of instruments required at a dam can only be addressed effectively by combining experience, common sense, and intuition. Dams present unique situations and require individual solutions to their instrumentation requirements. The instrumentation system design, therefore, needs to be planned with consideration for the site-specific geotechnical conditions present in the embankment, foundation, abutments, concrete structure, and reservoir rim. Reasons such as unique design or difficult foundation conditions, severe downstream hazard, visually observed problems or concerns, remoteness of location, normally unmanned operation, or other concerns justify providing instrumentation. Personnel installing field instrumentation must understand the fundamental physics and mechanics involved, and how the various available instruments will perform under the conditions to which they will be subjected.

As discussed earlier, a wide variety of devices and procedures are used to monitor dams, and the installation and operating details of most of the available instruments are beyond the scope of this manual. Therefore, this subchapter presents general guidelines for instrumentation and details for some of the simpler devices that most dam owners can readily deploy. Details of the installation, operation, and maintenance of each device are described in the following publications:

(1) *Embankment Dam Instrumentation Manual*, U.S. Bureau of Reclamation, Government Printing Office, February 1987.
(2) *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance*, American Society of Civil Engineers, September 2000.
(3) *Instrumentation of Embankment Dams and Levees*, EM 1110-2-1908, U.S. Army Corps of Engineers, June 1995.
(4) *Instrumentation for Concrete Structures*, EM 1110-2-4300, U.S. Army Corps of Engineers, November 1987.

Planning an instrumentation and monitoring system requires the consideration of many factors, and a team effort of the designers (or those responsible for evaluating existing projects) and personnel having expertise in the application of instrumentation. Developing an instrumentation system should begin with a definition of an objective and proceed through a comprehensive series of logical steps that include all aspects of the proposed system. Recommended steps for developing an instrumentation system are presented on Table 3-2.

Table 3-2
Steps for Developing an Instrumentation System

- Prediction of mechanisms that control dam behavior
- Definition of purpose of instrumentation
- Definition of geotechnical issues and concerns
- Selection of parameters to monitor
- Prediction of magnitude or range of changes being monitored
- Selection of instrument locations
- Selection of type and make of instruments
- Determination of need for automation
- Planning for recording of factors which influence measurements
- Establishment of procedures for ensuring data validity
- Determination of capital and operating costs
- Preparation of installation plan and schedule
- Planning long-term protection of instruments
- Planning regular calibration and maintenance
- Planning data collection and management
- Coordination of resources and assignment of responsibility
- Determination of life cycle costs

High hazard dams need to be closely monitored on a regular basis because of the potential safety risk they pose to the public. The minimum level of monitoring at every high hazard dam should include the following measures, as applicable:

- Measurement of reservoir water surface elevation (reservoir gage).
- Measurement of drainage and seepage flow rates.
- A survey control network with fixed monuments adjacent to the dam and on the embankment crest.
- A written plan that can allow the owner to monitor deformations and possible movement of dam structures at a moments notice.
- Detailed specifications and installation plans for each instrument that may be used.
- An operation and maintenance manual for each instrument that is used.

Instrumentation Usage by Function

For ease of reference, the most common types of equipment used are categorized based on the conditions most commonly encountered at dams. If the dam owner has a specific monitoring need, he/she should first determine what condition or conditions must be monitored; then, the type of instrument(s) that can be used to best suit the need should be determined. Monitoring equipment can be categorized by the following conditions:

- deformation or movements (horizontal, vertical, rotational, and lateral)
- groundwater pressure (pore pressure and uplift pressures)
- water level
- seepage flow
- water quality
- temperature
- cracks and joints
- seismic activity
- weather and precipitation
- stress and strain

Monitoring equipment that can be used for each of these conditions is described below. As discussed in Part 3 of the Indiana Dam Safety Inspection Manual, visual observations by the dam owner or the owner's representative may be the most important and effective means of monitoring the performance of a dam. The visual inspections should be made whenever the inspector visits the dam site and should consist of a minimum of walking along the dam alignment and looking for any signs of distress or unusual conditions at the dam.

<u>**Deformation or Movements**</u>

Deformation or movements occur in every dam. They are caused by stresses induced by reservoir water pressure, unstable slopes (low shearing strength), low foundation shearing strength, settlement (compressibility of foundation and dam materials), thrust due to arching action, expansion resulting from temperature change, and heave resulting from hydrostatic uplift pressures. Movements can be categorized by direction, including horizontal, vertical, rotational, and lateral.

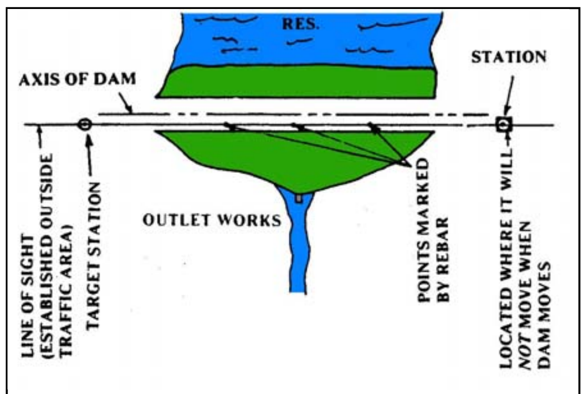

Figure 3-13a Schematic of survey control plan for monitoring alignment and settlement.

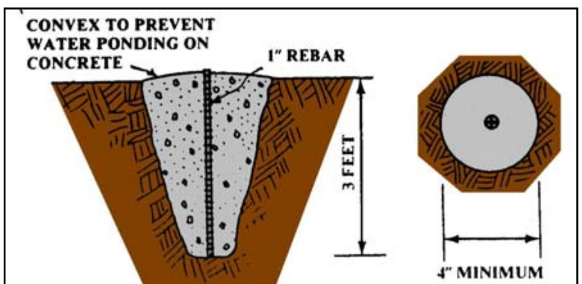

Figure 3-13b Schematic of section through a permanent survey monument. (Note that the sides of the monument should be vertical if frost heave is a concern.)

Monitoring movements (also called displacements) can be helpful in understanding the normal behavior of a dam as well as being useful in determining if a potentially hazardous condition is developing. The displacements are more commonly measured on the surface of the embankment or concrete structure. Measuring displacements of points on the surface is usually accomplished by conventional surveying methods such as leveling or alignment. The movements are not limited to just the embankment or dam, but can sometimes be traced to a point below the dam in the foundation. Internal displacement monitoring schemes can be complex and expensive. Therefore, the measurement of displacements is usually monitored on the surface, unless a problem develops.

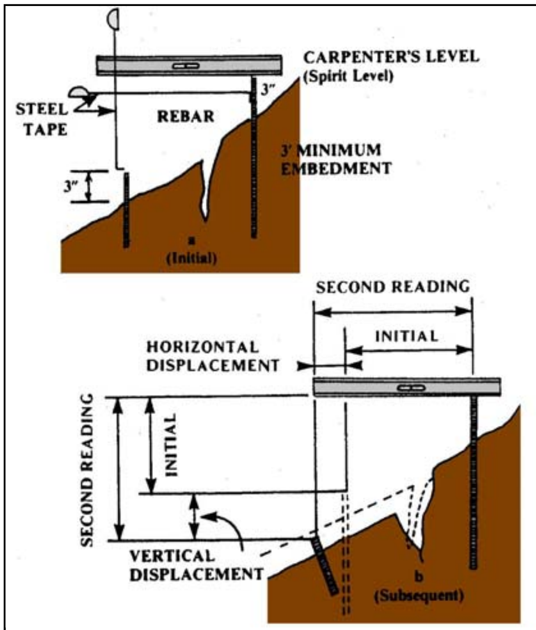

Figure 3-14 Simple system for monitoring cracks and slope displacement.

<u>Horizontal Movement</u>

Horizontal, or translational, movement commonly happens in an upstream-downstream direction in both embankment and concrete dams. It involves the movement of an entire dam mass relative to its abutments or foundation. Cracks are usually present during horizontal movement. Vertical, rotational, and lateral movements often occur in conjunction with horizontal movement.

In an embankment dam, instruments commonly used for monitoring horizontal movement include:

- extensometers
- multi-point extensometers
- inclinometers
- shear strips
- structural measuring points
- embankment measuring points

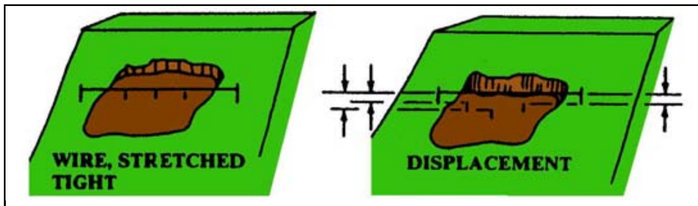

Figure 3-15 Simple technique for monitoring slides.

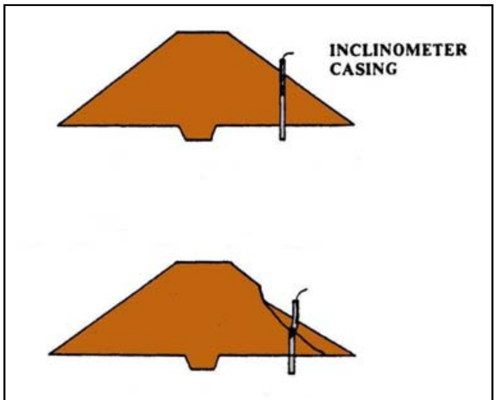

Figure 3-16 Inclinometer probes are used to detect horizontal displacement of the casing.

Installation of simple measuring points is an easy way to monitor horizontal movements. A simple system for monitoring displacements on the surface consists of a few permanent points across the crest of the dam (see Figures 3-13 a and b). The points are usually marked with a 3-foot length of 1-inch diameter rebar set in concrete. The alignment system measures the change in the point's position relative to the line of sight. Subsequent measurements are compared with the initial. The amount of horizontal displacement from the line-of-sight and the change in elevation (vertical movement) from the initial is reported. The rate of settlement and horizontal displacement with time or reservoir gage height can be observed. The single line-of-sight system can be expanded to include two or even three lines-of-sight to monitor points across the upstream and downstream face. More often the alignment monitoring system is used to establish behavior patterns of the dam especially during filling of the reservoir or during the construction of modifications to the dam.

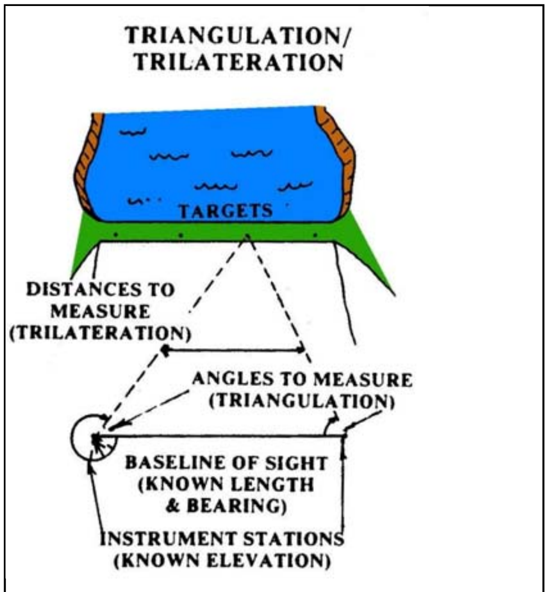

Figure 3-17a Schematic of triangulation/trilateration plan.

For dams with a long crest length, the line-of-sight can be excessively long. In this case, the line of sight is frequently moved downstream of the dam and becomes a baseline. Displacements are monitored by turning angles from fixed points, or stations, on the baseline to points on the dam. The system forms triangles and is known as triangulation. Instead of measuring angles, the horizontal distances between the end points of the baseline and points on the dam may be monitored using electronic distance measuring (EDM). The distance measuring scheme is known as trilateration. Triangulation and trilateration are strictly for horizontal control.

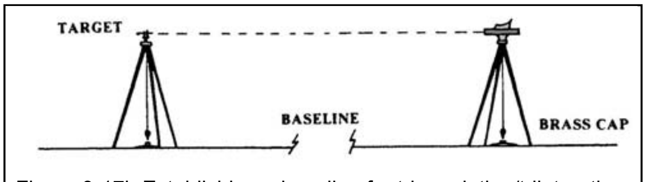

Figure 3-17b Establishing a baseline for triangulation/trilateration.

The survey instrument is positioned over the station. A target is placed on the other instrument station and at the point to monitor on the dam. Once the sight on the baseline is established the angle between the baseline and the line to the target is measured. After measuring angles to all targets, the instrument is moved to the other station and the other angles from the baseline to the targets are measured. The most common source of error typically is not having the instrument exactly plumb.

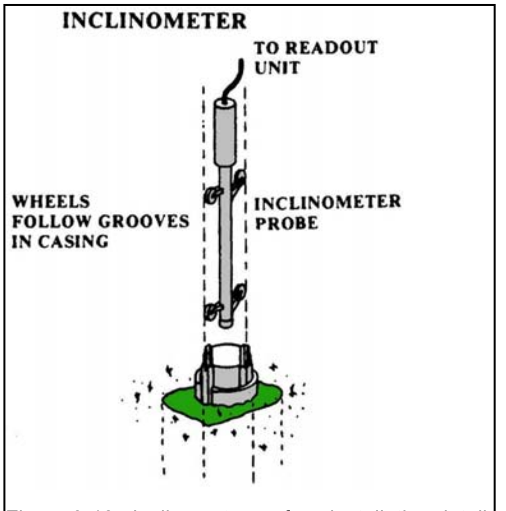

Figure 3-18a Inclinometer surface installation detail.

The owner is frequently faced with special situations where the temporary and immediate monitoring of potentially dangerous conditions is needed. Sometimes this calls for a little imagination on the part of the owner and the use of common materials.

A simple method of monitoring cracks on embankments is to drive rebar or stakes on both sides of the crack(s) to monitor any additional separation and vertical displacement on one side of the crack relative to the other side. Also, the

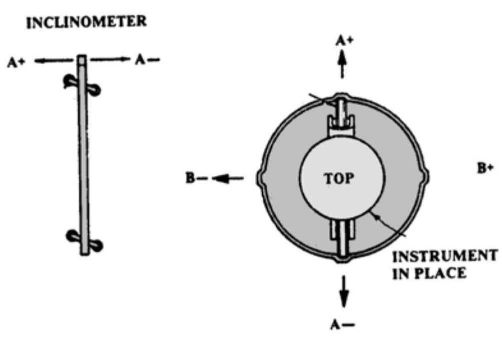

Figure 3-18b Inclinometer casing detail.

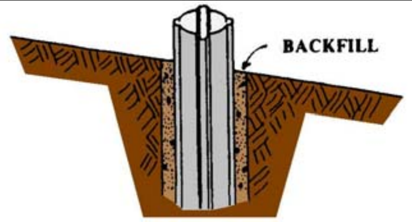

Figure 3-18c Inclinometer casing installation detail.

end of the crack should be staked to determine if the crack is lengthening. This scheme can be used to monitor both longitudinal and transverse cracking (see Figure 3-14).

Another special situation which would require immediate attention is a slide. The method of monitoring is simple yet reliable and utilizes the same principle as the alignment method. A strong wire is stretched across the slide and tied to pins outside the slide area. At intervals along the wire, pins are driven into the slide mass as shown on the left. If additional movement occurs, the amount is directly determined by measuring the distance between the pins and the wire (see Figure 3-15).

Inclinometers are used to monitor internal displacements of the embankment or movements in the foundation. The purpose and advantage of making measurements of internal movements are that the movements will undoubtedly be detected before the effects appear on the surface. The embankment and foundation deforms and causes the surface to move. Therefore, surface monitoring of displacements does not always tell the entire story of "what is happening." The inclinometer is designed to measure horizontal movements of the embankment and/or the foundation at any depth below the surface. The system consists of a special casing with grooves on the inside at the quarter points.

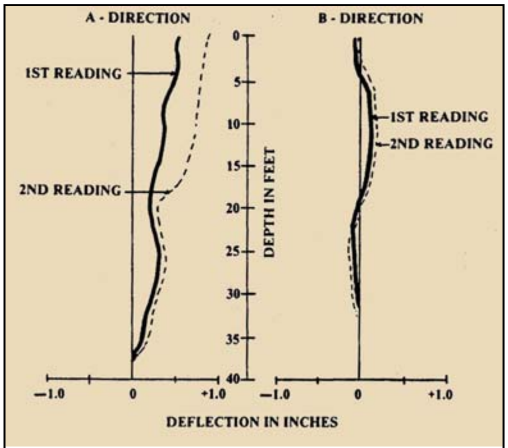

Figure 3-19 Plot of inclinometer readings.

The inclinometer is installed in the embankment portion of a dam. The inclinometer probe will detect small horizontal displacements of the casing. Many times the displacements are small but can be a sign of internal movement of the dam. Being able to detect small internal movements can warn against a large movement before it is observed on the surface as a crack or slide. The inclinometer readings should be plotted on a table or a graph, such as the one shown on Figure 3-19 to monitor the changes with time. A qualified dam safety professional should be consulted to determine the location and supervise the installation of inclinometers.

It should be emphasized that the more elaborate the scheme for monitoring surface movements, the more important it is to consult a qualified dam safety professional or land surveyor.

For a concrete dam, instruments for monitoring horizontal movements may include:

- crack measuring devices
- extensometers
- multi-point extensometers
- inclinometers
- structural measuring points
- tape gauges
- strain meters
- plumb lines
- foundation deformation gauges

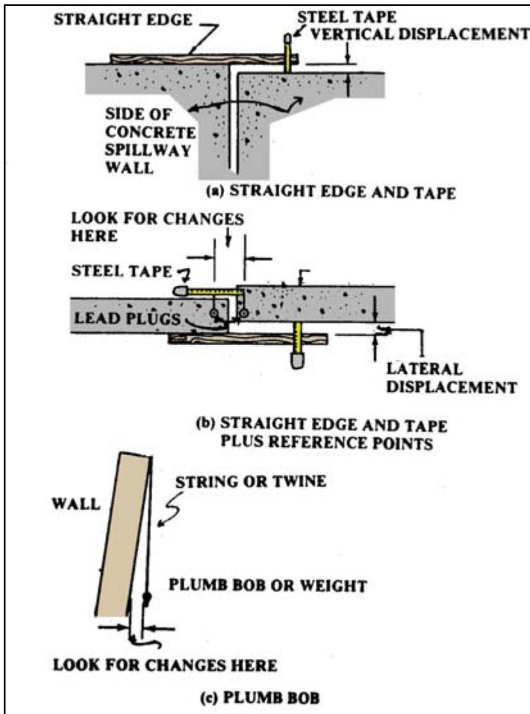

Figure 3-20 Simple method for monitoring concrete displacement.

The owner should also concentrate on monitoring changes in the concrete structures associated with the dam, such as the spillway and outlet works. The owner should monitor vertical and lateral displacements in addition to horizontal movement. Structural cracking and tilting of walls in spillways or the drop structure for the outlet are common forms of movement. Simple methods for monitoring movements on concrete structures are illustrated on Figures 3-20 and 3-21.

Vertical Movement

Vertical movement is commonly a result of consolidation of embankment or foundation materials resulting in settlement of the dam. Another cause is heave (particularly at the toe of a dam) caused by hydrostatic uplift pressures. In an embankment dam, vertical movements may be monitored by:

- settlement plates/sensors
- extensometers
- piezometers
- vertical internal movement devices
- embankment measuring points
- structural measuring points
- inclinometer casing measurements

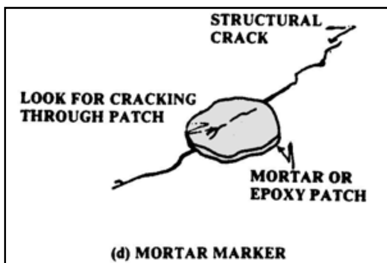

Figure 3-21 A concrete patch can be used to monitor movement.

In a concrete dam, vertical movement monitoring devices may include:

- settlement sensors
- extensometers
- piezometers
- structural measuring points
- foundation deformation gauges

<u>Rotational Movement</u>

Rotational movement is commonly a result of high reservoir water pressure in combination with low shearing strength in an embankment or foundation and may occur in either component of a dam. This kind of movement may be measured in either embankment or concrete dams by instruments such as:

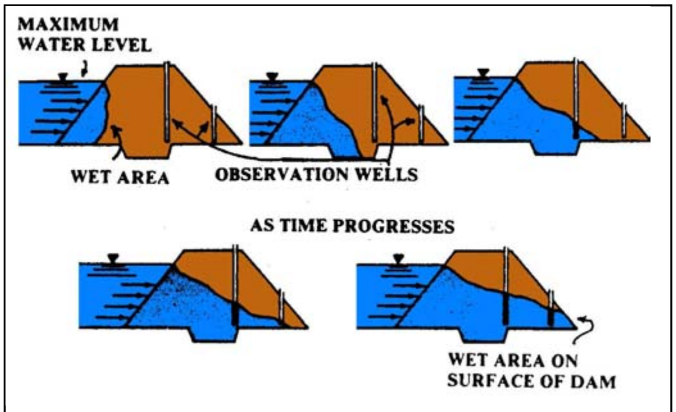

Figure 3-22 Observation wells can be used to monitor water levels, or phreatic surface, in the embankment.

- extensometers
- inclinometers
- tiltmeters
- surface measurement points
- crack measurement devices
- piezometers
- foundation deformation gauges
- plumb lines (concrete only)

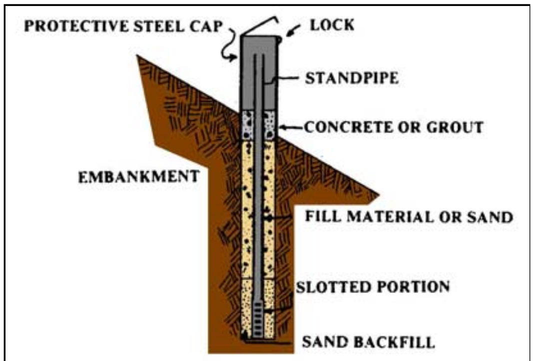

Figure 3-23 Schematic of observation well installation.

<u>Lateral Movement</u>

Lateral movement (parallel with the crest of a dam) is common in concrete arch and gravity dams. The structure of an arch dam causes reservoir water pressure to be translated into a horizontal thrust against each abutment. Gravity dams also exhibit some lateral movement because of expansion and contraction due to temperature changes. These movements may be detected by:

- structural points
- tiltmeters
- extensometers
- crack measurement devices
- plumb lines
- strain meters
- stress meters
- inclinometers
- joint meters
- thermometers
- load cells

Water Level

For most dams, it is important to monitor the water level in the reservoir and the downstream pool regularly to determine the quantity of water in the reservoir and its

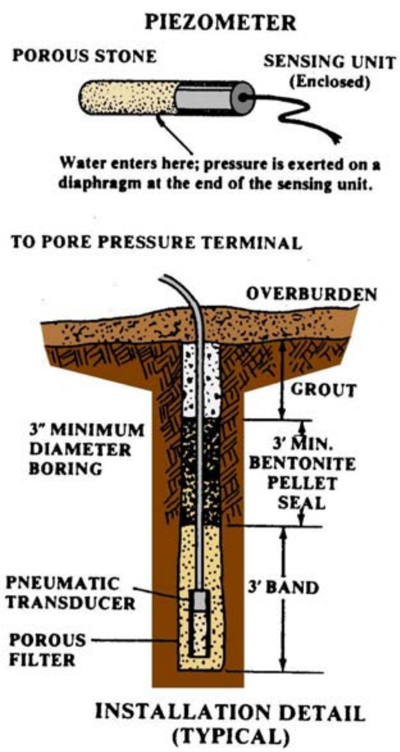

Figure 3-24 Piezometers are used to monitor groundwater pressure.

level relative to the regular outlet works and the emergency spillway. The water level is also used to compute water pressure and pore pressure; the volume of seepage is usually directly related to the reservoir level. It is also important to establish the normal or typical flow through the outlet works for legal purposes. Water levels may be measured by simple elevation gages (either staff gages or numbers painted on permanent, fixed structures in the reservoir), or by complex water level sensing devices.

Flow quantities can be computed from knowledge of the dimensions of the outlet works and the depth of flow in the outlet channel or pipe. Flow meters, flumes, and weirs can also be used if a more accurate determination is needed. A simple, inexpensive technique consists of using a bucket or other container of known volume and a watch to collect and measure the time it takes to fill the container.

Internal water levels must also be monitored to establish the phreatic surface within the embankment. Water in an earth embankment enters the observation well standpipe through the slotted portion and rises to the same level as the water in the soil around the observation well. Each reading of an observation well should be compared to previous readings. A change in the reading should be evaluated as follows:

1. Draw a profile of the water surface on the cross section of the dam along with the reservoir water surface.
2. If the profile appears normal or what can be expected for the current height of the reservoir water surface, continue the normal monitoring program.
3. If the profile appears unusual, it may indicate a potentially dangerous situation. Contact a qualified dam safety professional to discuss the results.
4. Graphs should also be maintained showing the entire history of the observation well measurements. The format of the graphs should make them easy to update after each measurement. This will enable the observer to see the relationship between the current reading and previous readings graphically.

Groundwater Pressure

Water seeps through, under, and around the ends of all dams. The water moves through pores in the soil, rock, or concrete as well as through cracks, joints, etc. The pressure of the water as it moves acts uniformly in all planes and is called pore pressure. The upward force (called uplift pressure) has the effect of reducing the effective weight of the downstream portion of a dam and can materially reduce dam stability. Pore pressure in an embankment dam, a dam foundation, or abutment, reduces that component's shearing strength. In addition, excess water, if not effectively channeled by drains or filters, can result in progressive internal erosion (piping) and failure. Pore pressures can be monitored with the following equipment:

- piezometers (electrical, open standpipe, pneumatic, hydraulic, porous tube, slotted pipe)
- pressure meters & gauges
- load cells

The components of open standpipe piezometers are identical in principle to components of an observation well, with the addition of subsurface seals which isolate the zone of interest. Readings can be made by sounding with a water level indicator, with a pressure transducer placed in the standpipe below the lowest piezometric level, or with a sonic transducer.

Unlike the observation well, which directly shows the height of water in the embankment or foundation, a piezometer indicates the pressure exerted by the height of water above the tip of the piezometer. The piezometer measures the pressure of water entering the porous filter stone in the well. In the case of an earth dam the pressure is primarily due to the infiltration of water into the embankment from the reservoir. The pressure exerted on the piezometer is a function of the height reached by the water in the embankment above the piezometer. The advantage the piezometer has over the observation well is the ability to measure small changes in the water level above it. A piezometer also has a more rapid response to changes of water pressure in the embankment. The piezometer can also sense changes in the water pressure created by factors other than increase in the water level in the embankment. A piezometer can be installed in the foundation under the embankment, or at any other level in the soil. A qualified dam safety professional should be consulted to evaluate the need and supervise the installation of piezometer. There are several types of piezometer available (i.e., open tube, hydraulic, pneumatic, electric, etc.). Selection of piezometers is made based on use, cost, and availability.

Twin-tube hydraulic piezometers utilize a twin-tube system to determine groundwater pressure. The piezometric elevation is determined by adding the pressure gage reading to the elevation of the pressure gages. If both tubes are completely filled with liquid, both pressure gages should indicate the same pressure. However, if gas has entered the system (through the filter, tubing, or fittings) the gas will cause an inaccurate pressure reading on one or both gages. The gas must be removed by flushing. Dual gages therefore indicate the need for flushing and re-calibration.

Pneumatic piezometers utilize the principle of differential gas pressure described earlier. A filter is added to separate the flexible diaphragm from the material in which the piezometer is to be installed. A special type of pneumatic piezometer is available for installation by pushing into foundation material, rather than by drilling and subsurface sealing. The piezometer is pushed below the bottom of a borehole, and the borehole is filled with a soft bentonitic grout. Great care must be taken during installation to avoid damaging the lead connection to the sensor.

Vibrating wire piezometers are based on the use of a pressure sensor. A filter is added, and permanent embedded installation arrangements can be similar to those for an open standpipe piezometer. Special heavy-walled versions are available for installation in compacted fills, the heavy wall ensuring that the instrument responds only to changes in pore water pressure, and not to total stresses acting on the housing. Special versions are also available, similar to the pneumatic piezometer, for monitoring consolidation pore water pressures below embankments where vertical compression of the foundation material is large.

Electrical resistance piezometers are based on the strain gages. The vent tubes have been known to block and invalidate readings.

All piezometers include an intake filter. The filter separates the pore fluid from the structure of the soil in which the piezometer is installed and must be strong enough to avoid damage during installation and to resist the total stresses without undue deformation. Filters can be classified in two general categories: high air entry and low air entry. Filters keep fluids in equilibrium by balancing the pressure differential with surface tension forces at the gas/water interface. The finer the filter, the greater can be the pressure differential. The air entry value or bubbling pressure of the filter is defined as the pressure differential at which blow-through of gas occurs. Thus, a filter with a high air entry value (or high bubbling pressure) is a fine filter that will allow a high pressure differential before blow-through occurs.

Low air entry filters are coarse filters that readily allow passage of both gas and water, and should be used for all piezometer types that are installed in saturated soils and for open standpipe piezometers installed in unsaturated soils. Filters should be saturated when installed. They can readily be saturated with water prior to installation by soaking or by passing water through the pores.

High air entry filters are fine filters that must be used when piezometers (except open standpipe piezometers) are installed in unsaturated soil, such as the compacted core of an embankment dam, with the intent of measuring pore water pressure as opposed to pore gas pressure, in an attempt to keep gas out of the measuring system. Saturation of high air entry filters requires a much more controlled procedure, entailing removal of the filter from the piezometer, placing the dry filter in a container, and applying a vacuum. The filter should then be allowed to flood gradually with warm de-aired water.

When using piezometers, reliability and durability are often of greater importance than sensitivity and high accuracy. Therefore, the designer's intent for the use of the instrument is crucial to the selection of the type of instrument. The fact that the actual head may be in error by as much as 1 ft, as a result of time lag, may not matter in some cases, provided the piezometer is functioning properly. Piezometer installations with transducers may require corrections for barometric pressure if high accuracy is needed.

For measurement of piezometric pressure in saturated soil, an open standpipe piezometer is the first choice and should be used when applicable. Limitations associated with extending the standpipe through embankment fill normally prevent their use within the fill of an embankment dam. When any of these limitations are unacceptable, a choice must be made among the remaining piezometer types.

For short-term applications, defined as applications that require reliable data for a few years (for example during the typical construction period), the choice is generally between pneumatic and vibrating wire piezometers. The choice will depend on the site factors, on the user's own confidence in one or the other type, and on a comparison of cost of the total monitoring program.

For long-term applications twin-tube hydraulic piezometers and Casagrande piezometers have become attractive options because of their basic simplicity and reliability.

For monitoring consolidation pore water pressures below embankments, in cases where vertical compression of the foundation material is large, the push-in pneumatic or vibrating wire piezometers are good choices. Push-in versions of open standpipe piezometers are also available.

When the economics of alternative piezometers are being evaluated, the total cost should be determined, considering costs of instrument procurement, calibration, installation, maintenance, monitoring, and data processing. The cost of the instrument itself is rarely the controlling factor and should never dominate the choice.

If the pores in a soil contain both water and gas, such as in the compacted clay core of an embankment dam or in an organic soil deposit, the pore gas pressure will be greater than the pore water pressure. In fine-grained soils, the pressure difference can be substantial, and special techniques are required to ensure measurement of pore water pressure rather than pore gas pressure. For all piezometer types other than open standpipe piezometers, these techniques include use of high air entry filters, saturated before use, with the filter in contact with the unsaturated soil. Intimate contact will not be achieved if the filter is on the flat end of a cylindrical piezometer; the filter must be on the side or on a conical end. The piezometer should not be installed in a sand pocket.

Piezometer selection criteria for a soil containing both water and gas are similar to those described earlier for saturated soil. For short-term applications, the choice will generally be among open standpipe, pneumatic, and vibrating wire piezometers. For long-term applications the longevity of filter saturation is uncertain because gas may enter the filter by diffusion. The compacted fill in an embankment dam may remain unsaturated for a prolonged period after the reservoir is filled, and in fact the fill may never become permanently saturated by reservoir water. Increase of water pressure causes air to go into solution, and the air is then removed only when there is enough flow through the fill to bring in a supply of less saturated water. The pressure and time required to obtain saturation depend on the soil type, degree of compaction, and degree of initial saturation. Pore gas pressure may therefore remain significantly higher than pore water pressure for a substantial length of time, perhaps permanently. Pneumatic and vibrating wire piezometers therefore cannot be relied upon for monitoring long-term pore water pressures. However, twin-tube hydraulic piezometers allow for flushing of the filter and cavity with de-aired liquid, thereby ensuring that pore water pressure continues to be measured. The choice for long-term reliable measurement of pore water pressure is therefore between open standpipe and twin-tube hydraulic piezometers.

Seepage Flow

The potential for a dam to leak, or seep, will vary according to the design of the embankment, the ability of the cutoff to prevent leakage under the dam, and the tightness of the natural abutments. Seepage should first appear at the toe drain if the dam was constructed with a drain system. If the dam does not have a drain system, seepage may appear on the downstream face.

Seepage should be monitored on a regular basis to determine if it is increasing or decreasing, or remaining constant as the reservoir level fluctuates. A flow rate changing relative to a reservoir water level can be an indication of a clogged drain, piping, or internal cracking of the embankment. Seepage may be measured using the following devices and methods:

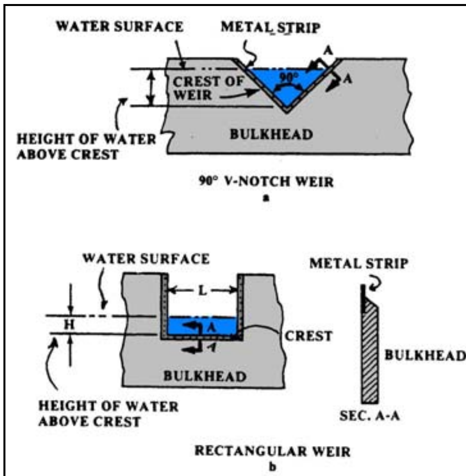

Figure 3-25 Schematic of common weirs.

- weirs (any shape such as V-notch, rectangular, trapezoidal, etc.)
- flumes (such as a Parshall flume)
- pipe methods
- timed-bucket methods
- flow meters
- observation Wells

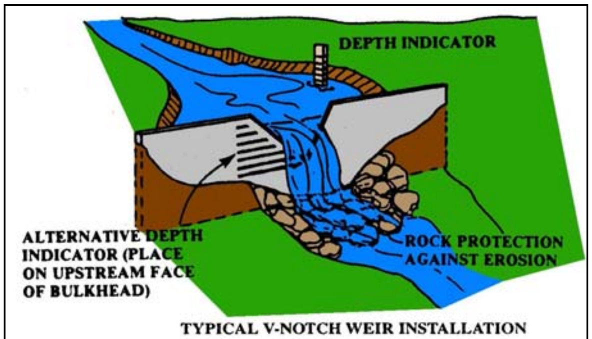

Figure 3-26 Typical V-notch weir installation.

Weirs, flumes, and dikes can be installed to measure seepage, especially seepage exiting from the embankment or foundation at random point sources. When properly calibrated and kept free of silt and vegetation, weirs and flumes can measure seepage accurately. These devices can also be used downstream of general seepage areas where the water flows into a ditch or channel. Weirs and flumes that are silted-in may indicate that the embankment or foundation material is being piped out of the dam, or sediment from surrounding surface runoff erosion is collecting in the structure. If weirs and flumes become silted-in, the situation should be carefully evaluated to determine the cause of the siltation. Dikes can be installed across a channel or ditch with a pipe installed to measure flow also, as shown in Figure 3-28.

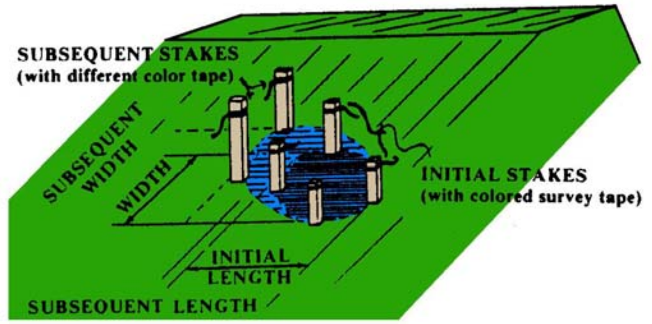

Figure 3-27 Simple technique for staking and monitoring seepage progression.

If the area is damp from seepage, the perimeter of the wet area should be staked out and the length and width of the area should be recorded. Also the degree of wetness, such as boggy, surface moist but firm underfoot, etc., should be described. An example of staking wet areas is shown on Figure 3-27.

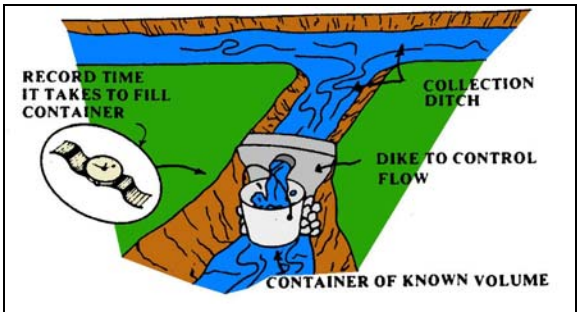

Figure 3-28 Measuring seepage flow with simple tools.

When the leak produces a measurable flow of water, the quantity should be monitored. First, confine the flow through drainage channels away from the embankment. Then measure the quantity flowing by creating a drop in the drainage channel and installing a pipe, a weir, or a flume. The most accurate and direct measurement can be obtained by catching the flow from a pipe in a container of known volume and timing how long it takes to fill the container as shown in Figure 3-28. The flow rate should be recorded in gallons per minute.

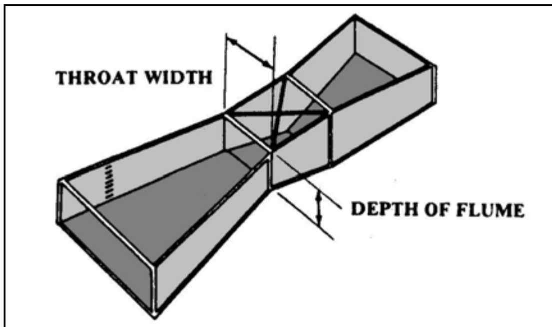

Figure 3-29 Schematic of Parshall flume.

A weir, on the other hand, can save time, but the measurement is not as direct as the bucket and stop watch. The rate of flow at a weir is related to the height of water flowing over the crest of the weir. The most commonly used are the V-notch and rectangular weirs.

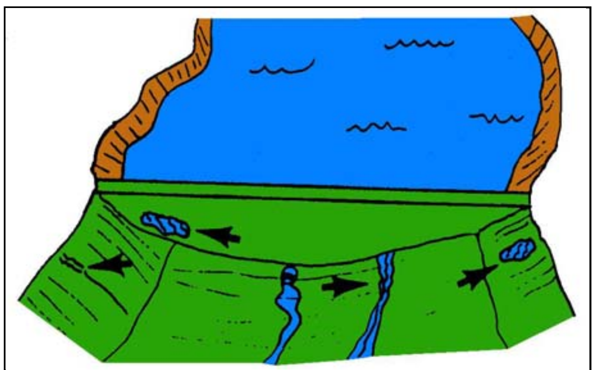

Figure 3-30 Drawing a sketch of seepage areas is a good way to record observed conditions.

For larger flows, the Parshall flume is preferred to larger weirs because the flume will not restrict the flow as much as the weir. Parshall flumes like that shown on Figure 3-29 can be purchased through a manufacturer and is shown here only as a guide to help the owner understand the methods used to measure seepage quantities. Table 3-5 presents approximate

Table 3-3 Discharge of 90-degree V-Notch Weirs

Head, H in Ft	Approx. Flow In GPM	Head, H in Ft	Approx. Flow In GPM
0.10	4	0.42	129
0.12	6	0.44	145
0.14	8	0.46	162
0.16	12	0.48	180
0.18	16	0.50	200
0.20	21	0.52	220
0.22	26	0.54	241
0.24	32	0.56	264
0.26	39	0.58	288
0.28	47	0.60	314
0.30	56	0.62	340
0.32	66	0.64	368
0.34	77	0.66	397
0.36	88	0.68	428
0.38	101	0.70	460
0.40	115	0.72	493

Table 3-4 Discharge of Standard 1-ft Contracted Rectangular Weir

Head, H in Ft	Approx. Flow In GPM	Head, H in Ft	Approx. Flow In GPM
0.02	4	0.28	209
0.04	12	0.30	231
0.06	22	0.32	253
0.08	33	0.34	276
0.10	46	0.36	300
0.12	61	0.38	324
0.14	76	0.40	348
0.16	93	0.42	373
0.18	110	0.44	398
0.20	128	0.46	423
0.22	147	0.48	449
0.24	167	0.50	476
0.26	188		

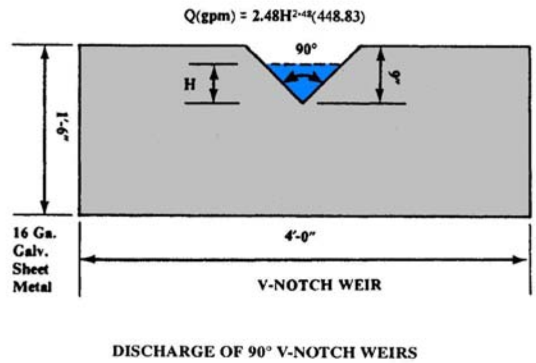

Figure 3-31 Dimensions of 90-degree V-notch weir.

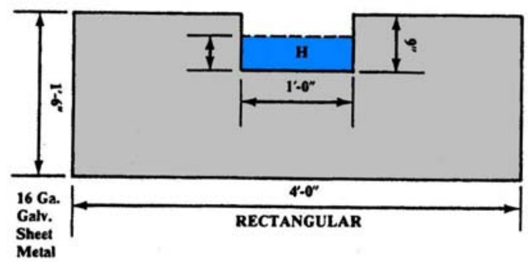

Figure 3-32 Dimensions of rectangular weir.

Table 3-5 Typical dimensions of Parshall flumes.

Rated Capacity		Throat Width	Depth	Weight	Thickness	Intake Width	Overall Length
cfs	gpm	In.	In.	Lbs	gage	In.	ft
0.082	32	1	6	13	16	6.59	2.08
0.469	210	2	10	25	16	8.41	2.54
0.640	287	3	12	55	12	10.19	3.00
1.134	509	3	18	41	16	10.19	3.00

flow quantities for some Parshall flumes of various sizes.

The reservoir gage rod height should be recorded along with seepage quantities. It is also helpful to have a site map or sketch describing the location and extent of the seepage similar to the sketch shown on Figure 3-30. All pertinent features of topography and sources which may be contributing to the seepage should be included on the map or sketch. A photograph of the seepage or wet area is also helpful in describing the situation.

Water Quality

Seepage comes into contact with various minerals in the soil and rock in and around the dam. This can cause two problems: the chemical dissolution of a natural rock such as limestone, or the internal erosion of soil. Dissolution of minerals can often be detected by comparing chemical analyses of reservoir water and seepage water. Such tests are site specific; for example, in a limestone area, one would look for calcium and carbonates; in a gypsum area, calcium and sulfates. Other tests, such as ph can also sometimes provide useful information on chemical dissolution. Internal erosion can be detected by comparing turbidity of reservoir water with that of seepage water. A large increase in turbidity indicates erosion.

Figure 3-33 Turbid water exiting a pipe under an embankment.

An accurate measurement of leakage quantities along with changes in the turbidity and amount of sediment in the water may be an indication of the beginning or progression of piping. Turbidity is a measure of the amount of soil particles suspended in the water. A visual description would be the color, e.g., clear, cloudy, etc. The sediment will usually be larger particles (silt, sand, small gravel) which settle out in a jar sample of the water. An increase in the turbidity or sediment may indicate that the water is carrying soil with it as it travels through the dam, a very dangerous condition. Each time the quantity is measured, an evaluation of the turbidity and sediment should be made to observe any change. The easiest method of comparing observations is to collect a sample of the water in a quart jar marked with the date collected and retain the sample. A different jar should be used until five or six samples have been collected. Then the jars can be reused, starting with the one containing the oldest sample. This way each new sample can be compared with the previous samples to observe any change in the turbidity or amount of sediment in the water. The water can be removed and the amount of sediment in the bottom of the jar can be weighed for a more accurate measurement.

A good way of detecting a change in turbidity is to collect a number of water samples as follows:

(1) Collect a sample of the water in a quart jar. Date the jar and note the level of clarity. Store the jar in a safe location.
(2) Repeat step 1 each time seepage flow is measured until several samples have been collected.
(3) Each time a sample is collected, shake up each jar and visually compare the new sample with the samples collected previously. Look for changes in the cloudiness of the samples. Also note the amount of sediment that accumulates in the bottom of the jars as suspended material settles out.

If seepage is clear, but it is suspected that it contains dissolved material from the foundation (because, for instance, seepage has increased without any signs of turbidity), it may be necessary to perform water quality testing.

The rate and turbidity of seepage flow should be recorded at each inspection. If seepage problems are suspected, then the frequency of inspections should be set by a qualified dam safety professional. If seepage problems do occur, further testing should be conducted by a qualified dam safety professional.

Temperature

The internal temperature of concrete dams is commonly measured both during and after construction. During construction, the heat of hydration of freshly placed concrete can create high stresses which could result in later cracking. After construction is completed and a dam is in operation, it is not uncommon for very significant temperature differentials to exist depending on the season of the year. For example, during the winter, the upstream face of a dam remains relatively warm because of reservoir water temperature, while the downstream face of the dam is reduced to a cold ambient air temperature. The reverse is true in the summer. Temperature measurements are important both to determine: causes of movement due to expansion or contraction and to compute actual movement. Temperature measurements can be made by using any of several different kinds of embedded thermometers or by making simultaneous temperature readings on devices such as stress and strain meters which provide means for indirectly measuring temperature of the mass.

Cracks and Joints

Knowledge of the locations and widths of cracks and joints in concrete dams, in concrete spillways, and other concrete appurtenances of embankment dams is important because of the potential for seepage through those openings. It is even more important to know if the width of such openings is increasing or decreasing. Various crack and joint measuring devices are available, and most allow very accurate measurement. Some use simple tape or dial gauges, while others use complex electronics to gain measurements.

Concrete cracks can be measured with a crack comparator, which is a hand held microscope with a scale on the lens closest to the surface being viewed. The scale includes lines of various thicknesses which can be compared to the crack. A more simple form of comparator consists of a clear plastic card printed with lines of various thicknesses. Crack movement can be measured with a crack measuring device which is attached to the concrete structure at the crack. This device gives direct readings of crack displacement and rotation.

Underwater inspection and measurement of concrete may be performed by divers, or by manned or unmanned underwater vehicles for very deep water conditions. Either way, cracks on the concrete surfaces can be photographed, videotaped, or measured with measuring tools.

As mentioned earlier, cracks are usually associated with movements, and the measurement of the crack widths and lengths is an indication of the amount of movement.

Seismic Activity

Seismic measuring devices record the intensity and duration of large-scale earth movements such as earthquakes. Many federal and state dams use these instruments because they are part of the U.S. Geological Survey's network of seismic recording stations. It may or may not be necessary for a private dam to contain any seismic devices depending upon whether it is in an area of significant seismic risk. Seismic instruments can also be used to monitor any blasting conducted near a dam site.

Weather and Precipitation

Monitoring the weather at a dam site can provide valuable information about both day-to-day performance and developing problems. A rain gauge, thermometer, and wind gauge can be easily purchased, installed, maintained, and monitored at a dam site.

Stress and Strain

Measurements to determine stress and/or strain are common in concrete dams and to a lesser extent, in embankment dams. The monitoring devices previously listed for measuring dam movements, crack and joint size and temperature are also appropriate for measuring stress and strain. Monitoring for stress and strain permits very early detection of movement. Earth pressure cells may be installed at the contact between the structure and soil during construction to measure stress.

Monitoring Frequency

The frequency of instrument readings or making observations at a dam depends on several factors including the following factors:

- relative hazard to life and property that the dam represents
- height or size of the dam

- relative quantity of water impounded by the dam
- relative seismic risk at the site
- age of the dam
- frequency and amount of water level fluctuation in the reservoir

In general, as each of the above factors increases, the frequency of monitoring should increase. For example, very frequent (even daily) readings should be taken during the first filling of a reservoir, and more frequent readings should be taken during high water levels and after significant storms and earthquakes. As a rule of thumb, simple visual observations should be made during each visit to the dam and not less than monthly. Daily or weekly readings should be made during the first filling, immediate readings should be taken following a storm or earthquake, and significant seepage, movement, and stress-strain readings should probably be made at least monthly.

CHAPTER 4.0

DAM MAINTENANCE AND REPAIR

4.0 DAM MAINTENANCE AND REPAIR

4.1 OVERVIEW

A good maintenance program can protect a dam against deterioration and prolong its life. A poorly maintained dam will deteriorate and may eventually lead to failure. Therefore, all dams should have an effective, well planned maintenance program. Nearly all the components of a dam and the materials used for dam construction are susceptible to damaging deterioration if not properly maintained. A good maintenance program provides protection for the owner and for the general public as well, especially property owners located downstream. The cost of a proper maintenance program is small compared to the cost of major repairs, loss of life and property, and resultant litigation.

Two different types of maintenance operations should be performed at all dams: (1) preventive maintenance, sometimes referred to as routine, or scheduled maintenance, and (2) repair maintenance, sometimes referred to as unscheduled maintenance. Preventive maintenance should be scheduled and performed at a regular frequency. It normally includes the same items each time, such as mowing grass and removing brush, repair of minor erosion rills, removal of burrowing animals, reseeding bare areas, riprap replacement, lubrication and/or painting of mechanical devices, etc. The dam O&M plan should itemize all routine maintenance items, including a description of the work, a schedule, and the resources required to perform the work. Repair maintenance is the work required to correct deficiencies that are discovered during inspections or emergencies. This type of maintenance can not be scheduled until it is observed, and may be unpredictable. Repair maintenance may include such things as repair of embankment slides, removal of large trees from the embankment, replacing a trash rack, repairing significant embankment settlement or erosion, etc.

Dam owners should develop a schedule for preventive maintenance and incorporate it into the O&M plan for the facility. In general, it is recommended that the entire program of preventive maintenance be performed at least twice per year. Preferably, preventive maintenance should be performed once in the spring, soon after winter snowmelt, and once in the late fall, sometime before the first snowfall. In addition, each dam owner should assess whether his facility has areas or items which require maintenance on a more frequent basis (i.e., daily, weekly, or monthly). For example, mowing may need to be performed more frequently.

Repair maintenance needs to be prioritized so that it is completed in a timely manner. Repair maintenance is a task which should never be neglected. If it is, the damage could get worse, requiring more extensive and more costly repairs.

Table 4-1 summarizes the various problems or conditions that might be encountered at a dam, categorized by relative priority. This table can be used by dam owners to help them prioritize their own maintenance repairs.

Table 4-1 Summary of Potential Maintenance by Priority

(1) Preventive maintenance (These tasks should be performed on a continuing basis)

- Routine mowing and general maintenance
- Maintenance and filling of cracks and joints on concrete dams
- Observation and monitoring of springs or areas of seepage
- Inspection of the dam (as discussed in Part 3)
- Monitoring of development in the watershed which would materially increase runoff from storms
- Monitoring of development downstream and updating the emergency notification plan to include new homes or other occupied structures within the area
- Monitoring and evaluation of instrumentation (if installed)

(2) Repair Maintenance (These tasks should be repaired as soon as possible, as indicated)

Immediate maintenance (The following conditions are critical and call for immediate attention)

- A dam about to be overtopped or being overtopped
- A dam about to be breached (by progressive erosion, slope failure, or other circumstances)
- A dam showing signs of piping or internal erosion indicated by increasingly cloudy seepage or other symptoms
- A spillway being blocked or otherwise rendered inoperable, or having normal discharge restricted
- Evidence of excessive seepage appearing anywhere at the dam site (an embankment becoming saturated, seepage exiting on the downstream face of a dam) increasing in volume.

Although the remedy for some critical problems may be obvious (such as clearing a blocked spillway), the problems listed above generally require the services of a Professional Engineer familiar with the construction and maintenance of dams. The emergency action plan (EAP) should be activated when any of the above conditions are noted.

Required maintenance at earliest possible date - The following maintenance should be completed as soon as possible after the defective condition is noted:

- All underbrush and trees should be removed from the dam, and a good grass cover should be established
- Eroded areas and gullies on embankment dams should be restored and reseeded as soon as weather permits
- Defective spillways, gates, valves, and other appurtenant features of a dam should be repaired
- Deteriorated concrete or metal components of a dam should be repaired as soon as weather permits

This chapter is intended to provide a guide and reference to all individuals performing dam maintenance. Each subchapter covers a specific type of maintenance (e.g, vegetation, erosion, seepage), and includes both preventive and repair maintenance. Complex repair work may require additional reference or expertise, and may require the help of a qualified dam safety professional. The dam owner or inspector should use the results of inspections to help identify any dam maintenance and repair work that may be required. Quick corrective action to conditions requiring attention will promote the safety and extend the useful life of the dam while possibly preventing costly future repairs.

If dam repairs involve significant modifications, such as replacing the spillway structures or altering the embankment, IDNR approval may be required. It is a good idea to consult with IDNR Division of Water personnel before any major work is performed on dams that are under IDNR jurisdiction.

Every dam owner should develop a basic maintenance program based on systematic and frequent inspections. As noted in Part 3, inspections should be performed on a regular basis, and after major flood or earthquake events. Dam inspectors and operating personnel should prepare a list of items requiring maintenance or repair along with recommendations, priorities, and schedules every time a dam is inspected.

4.2 VEGETATION

4.2.1 Grass

The establishment and control of proper vegetation is an important part of dam maintenance, and is required under Indiana Code 14-27-7.5. Properly maintained vegetation can help prevent erosion of the embankment and earth channel surfaces, and aid in the control of groundhogs and muskrats. The uncontrolled growth of vegetation, or inappropriate vegetation, can damage embankments and concrete structures and make close inspection difficult.

Figure 4-1 Embankment with excellent grass cover on upstream slope.

Grass vegetation is an effective and inexpensive way to prevent erosion of embankment surfaces. Grass is the only vegetation that is recommended for use on dam embankments. If properly maintained, it also enhances the appearance of the dam and provides a surface that can be easily inspected. Roots and stems tend to trap fine sand and soil particles, forming an erosion resistant layer once the plants are well established. Grass vegetation is least effective in areas of concentrated runoff, such as the contact of the embankment and abutments, or in areas subjected to wave action. Types of grass vegetation that have been used on dams in Indiana are fescue, rye grass, bluegrass, Bermuda grass, brome and reed canary grass. Sericea Lespedeza and crown vetch are not recommended in the spillway or on the dam embankment. IDNR permission may be required to use tall fescue.

Establishing vegetation on a dam depends on where the dam is located, the type of soil, the steepness of slope, and the orientation of the embankment. The vegetation proposed for the groin area and emergency spillway areas where there is flowing water might be different than the vegetation proposed for the steep slopes of the embankment. Owners may wish to contact the local field office of the Natural Resource Conservation Service (formerly Soil Conservation Service) or the local county extension office for recommendations on the establishment of this vegetation.

Maintaining a good, thick grass cover on an embankment dam at an appropriate height is one aspect of maintaining and keeping a dam safe. A dam is like any other man-made structure that creates a hazard; it needs to be maintained for safety and proper performance.

The purpose of keeping a healthy stand of grass at an appropriate height year round on the embankment and spillway is to: 1) protect the surface from extreme runoff events; 2) create a continuous, stable, near surface soil layer; 3) minimize woody/animal penetrations; 4) allow visual monitoring for early detection of safety deficiencies (seepage, wet spots, cracks, settlement, bulges, misalignment, sloughs, rills, holes, etc.) by the owner; and 5) prevent deterioration of the deeper compacted soils of the embankment.

A uniform, vigorous, turf forming grass stand that can tolerate stressful conditions (drought to very wet), survive high flows from runoff, provide protection to the underlying soil and allows for visual inspection of the structure is acceptable. A turf-type tall fescue would be an acceptable seed to use. Other grasses included in the mixture should be suitable for erosion control and steep slopes.

Grasses that are substantially clumpy, extremely deep-rooted, matt, spread or intertwine on the surface are not acceptable. Extremely deep-rooted grasses may compromise the integrity of the compacted embankment fill. A dense matted grass that creates a tangled mass will hide surface deficiencies and cause difficulty for the owner to routinely inspect and monitor the structure.

Crown vetch (Coronilla varia), a perennial plant with small bi-colored (pink and white) flowers is not recommended on dams. Crown vetch obscures the embankment surface, preventing early detection of cracks, erosion, and other damage. Large weeds, brush and trees can become established and periodic hand labor is then required to remove unwanted tall vegetation. Crown vetch is not effective in preventing erosion in some areas and is also expensive to establish.

Sericea Lespedeza (Lespedeza cuneata), an upright perennial summer legume is not recommended for use on dams or spillways. Sericea Lespedeza grows to a height of 3 to 5 feet. It grows in clumps, attracts burrowing animals, and obscures the surface of the dam. Sericea Lespedeza is not effective in preventing surface erosion.

Before seeding unvegetated areas, fertilizer and lime should be applied. Exact quantities necessary will vary with soil type and condition, and can be determined by having the soil tested. The fertilizer and lime should be raked, disked, or harrowed into the soil to a depth of not less than 4 inches. Periodic fertilization may be necessary to maintain vigorous vegetation.

The seed should be thoroughly mixed and evenly sown. The rate of seeding depends on the type of seed, percent purity, percent germination, and whether or not it is being incorporated into a seedbed, or applied as a dominant seeding on top of the ground. The seed should be covered with soil to a depth of approximately 1/4 inch, or rolled sufficiently. Immediately following planting, the area should be mulched with hay or straw at a rate of 2 to 3 tons per acre. Mulching materials should be kept in place with a mulch anchoring device or with asphalt emulsion. Steep slope areas may require the use of temporary or permanent erosion control fabric.

Weeds can prevent the growth of desirable grasses and should be eliminated or avoided. Once weeds become established, they are difficult to remove or control.

Establishing a good growth of grass will help prevent the growth of weeds.

Proper, routine maintenance is essential to keep the "design/spec" grass cover in a healthy condition to obtain the expected performance. Poor care and maintenance allow undesirable grasses, weeds and woody growth to overcome the acceptable grass.

Establishment and maintenance of the grass is fully as important as the engineering design of the dam. To develop good grass cover requires proper establishment and maintenance techniques such as fertilizer applications, mowing, spraying, cutting of brush and reseeding bare spots.

4.2.2 Trees and Brush

Trees and brush should not be permitted on embankment surfaces or in vegetated earth spillways. Extensive root systems can provide seepage paths for water. Trees that blow down or fall over can leave large holes in the embankment surface that will weaken the embankment and can lead to increased erosion or dam breaching. Trees and brush obscure the surface limiting visual inspection, provides a haven for burrowing animals, and retards growth of grass vegetation. Tree and brush growth adjacent to concrete walls and structures may eventually cause damage and should be removed. Some root systems can decay and rot, providing passageways for water, and thus cause erosion. Growing root systems can lift concrete slabs or structures, and can penetrate and damage drain systems. Trees and brush that are within 25 feet of the dam should be removed.

Figure 4-2 Embankment dam with excessive vegetation (trees) on downstream slope

Most tree roots are located in the top 6 to 24 inches of the soil and occupy an area of two to four times the diameter of the tree crown. The roots are located in this soil horizon because that's where most of the water, oxygen, and soil nutrients can be found. The roots obtain water, oxygen, and minerals from the soil; they do not grow "toward" anything or in any particular direction. Root systems consist of large perennial roots and smaller, short-lived, feeder roots. The large woody tree roots and their primary branches increase in size and grow horizontally. They are predominately located in the top 6 to 24 inches of the soil and usually do not grow deeper than 3 to 7 feet. Functions of the large roots include water and mineral conduction, food and water storage, and anchorage. These are the roots that can cause seepage problems in the dam embankments. Feeder roots average about 1/16 inches in diameter and constitute the major portion of the root system's surface area. These smaller roots grow outward and predominately upward from the large roots near the soil surface, where minerals, water, and oxygen are relatively abundant. The major function of the feeder roots is the absorption of water, oxygen, and minerals. Under normal conditions, these roots die and are replaced on a regular basis. Sometimes trees will develop tap roots, however, they usually do not. Oak trees, walnut, and ash trees will frequently grow a tap root, whereas maples, ash, fir, birch, and cottonwood trees often do not. Tap roots will only grow where soil conditions are favorable, depending on moisture, oxygen supply, soil texture, obstacles, other roots, and animals. Root systems are modified by their environment; more roots will grow in more favorable the soil conditions. Tap roots are rarely found in areas where the sub-soils are very dense or heavily compacted.

The following guidelines should be used when removing trees from dams:

Small trees (less than 6 to 12 inches)

- cut flush, remove all trunk and branches from site
- treat stump if possible to prevent regrowth

Large trees (greater than 6 to 12 inches)

- lower water level in reservoir to safe level
- remove tree, stump, rootball, and perennial roots (depending on location)

upstream slopes
- remove rootball
- excavate a bench where rootball was extracted
- backfill bench with compacted, cohesive soil
- install wave erosion protection

crest
- remove rootball and major roots
- clean rootball cavity
- backfill rootball cavity with compacted, cohesive soil
- plant grass

steep downstream slopes (> 2.5H:1V)
- cut trees with 2 to 3-ft stumps
- extract stumps with rootball
- remove roots during benching
- flatten slopes with compacted, cohesive soil
- install embankment toe drain system

moderate to flat downstream slopes (< 2.5H:1V)
- upper 1/3 of slope height
  - ► use same procedure as crest of dam
- middle 1/3 of slope height
  - ► remove rootball and major roots
  - ► clean rootball cavity
  - ► backfill rootball cavity with compacted, cohesive soil, or

install a filtered drain system
- ► plant grass where necessary
- ● lower 1/3 of slope height
  - ► use same procedure as steep downstream slopes

beyond toe of downstream slopes
- ● remove rootball and major roots
- ● clean rootball cavity
- ● install a filtered drain system or weighted filter system
- ● plant grass where necessary

Rodent habitats can develop when brush is cut down, so the cuttings should be removed from a dam to permit a clear view of the embankment. Following removal of large brush or trees, the left over root systems should also be removed if possible and the resulting holes properly filled. In cases where they cannot be removed, root systems can be treated with herbicide (properly applied) to retard further growth. After the removal of brush, cuttings may need to be burned. If this is done, dam owners should notify the local fire department, forest service, or other agency responsible for fire control.

4.2.3 Maintenance of Vegetation

Embankments, areas adjacent to spillway structures, vegetated channels, and other areas associated with a dam require continual maintenance of the vegetative cover. Grass mowing, brush cutting, and removal of woody vegetation (including trees as described above) are necessary for the proper maintenance of a dam. All embankment slopes and vegetated earth spillways should be mowed at least twice a year. Mowing promotes the formation of a sod, prevents trees and brush from growing, and gives a neat well kept appearance to the dam. Aesthetics, unobstructed viewing during inspections, maintenance of a non-erodible surface, and discouragement of groundhog habitation are reasons for proper maintenance of the vegetal cover.

Many methods are available for vegetation control. Acceptable methods include the use of weed whips or power brush-cutters and mowers. Chemical spraying to first kill small trees and brush is acceptable if precautions are taken to protect the local environment. Manufacturer’s recommendations should be followed when using chemical herbicides.

A wide variety of tools, attachments, and power equipment is available for satisfactory maintenance of vegetation. Hand-held brush cutters or weed whips range in weight from about 13 to 28 pounds. Cutting widths range up to about 21 inches, and there are various cutting blades including nylon string, plastic blades, and metal knife blades. These units can be used to cut grass, brush, woody vegetation up to 4 inches in diameter and can be used on almost any slope. Hand mowers are available in both push and self-propelled models. Width of cut varies up to a maximum of about 36 inches while maximum cutting height is about 4 inches. Hand mowers can be used safely on many slopes.

Garden and lawn tractors are available from 10 horsepower to a maximum of about 20 horsepower. They can be provided with wheels of different widths and with turf or agricultural tires. These type tractors may be equipped with four-wheel drive. Self-leveling units are also available for use on slopes. Power take-off drives are available for attachment to mowers and other accessories. Tractor speeds range to a maximum of about 7 miles per hour. Mower units are normally rotary, but pull-type flail and reel-type units are also available. Cutting height is a maximum of 7 inches and width of cut is from 36 to 60 inches. A garden tractor equipped with a 48-inch mower can mow about 1 acre an hour, depending on the slope and thickness of vegetation.


Figure 4-3 A lawn tractor being used to cut grass on an embankment dam.

Large farm tractors are available in engine sizes ranging from 22 horsepower up to 50 horsepower and higher. They are available in low profile models with four-wheel drives, self-leveling units for use on slopes, adjustable front and rear wheel widths, agricultural or turf tires, and power take-off drives for various accessory units. Maximum speeds are around 12 miles per hour. Mowing units, including rotary, reel, flail, and sickle bar types, are available for the large tractors. The tractor horsepower should be matched to the mowing unit needed for the job per the manufacturer's recommendations. The garden and farm tractors described in this manual cannot be used safely on slopes steeper than 2.5H:1V (40% or 21.80-degree slope). The larger tractors should be obtained with the lowest profile (or center of gravity) necessary for the type of slope to be mowed. Dual wheels or wider tires can be used to increase stability. All of these units should be equipped with safety roll bars designed to support the full weight of the tractor.

Self-contained mowing units are also available with self-leveling suspension for mowing very steep slopes. It is important to remember to use the proper equipment for the slope and type of vegetation to be cut, to always follow the manufacturer's recommended safe operation procedures, and not to mow when the vegetation is wet. Mowing should be done horizontally to prevent the formation of ruts aligned with the slope. Ruts can channel runoff and form erosion gullies.

Livestock should not be allowed to graze on the grass on the embankment surface. When the soil is wet, livestock can damage the vegetation and destroy the smooth surface resulting in ponded water or erosion from concentrated runoff. The resulting rough surface is difficult to mow. Cattle also tend to walk in paths killing the vegetation and forming channels for runoff. Livestock paths should be graded, seeded, and mulched. Livestock should be fenced off the dam and spillways.

No vehicles, other than maintenance vehicles, should be allowed on embankments. Maintenance vehicles should be kept off the embankment when it is wet to minimize rutting and damage to the vegetation.

Listed below are some considerations in maintaining the grass cover on the dam and spillway. There may be other site-specific factors that need to be considered.

- Grass on significant or high hazard dams or on dams that are a valuable resource should be mowed not burned. Burning a dam leaves the surface of the ground exposed to erosion for an extended period of time. Further, burning may overstress the design/spec grass and allow undesirable vegetation to establish.
- Mowing frequency will depend on what the turf can stand. Mowing just after seed has formed but before maturity will slow the growth of the turf for the rest of the summer. This would allow for good inspection and not cause as frequent of mowing.
- Mowing to six (6) inches is acceptable if the above item is followed. Mowing off no more than 1/3 of the leaf blade is standard for good turf management. By mowing off more, the turf is stressed and its growth slowed. Care must be taken not to stress the turf unduly by improper maintenance.
- Proper mowing equipment should be used to minimize rutting the slope, reduce damage to the grass, and provide safety for the operator.
- Slope trash (logs, stones, etc.) should be removed and ruts filled with compacted (similar) soil material to provide a uniform cut an4 minimize equipment damage and injury to the operator.
- Thick grass clippings or large clumps should be removed to keep the underlying grass from dying.
- After each mowing, the dam owner should thoroughly inspect the dam for deficiencies. If there are new deficiencies or significant changes in previous deficiencies, the dam owner's engineer and the Division of Water should be contacted.
- Bare spots should be seeded and fertilized. Weeds and woody growth should not be allowed to establish.

4.3 EROSION

Erosion of slopes, abutments, and spillway discharge channels is one of the most common maintenance problems with embankment structures. Erosion is a natural process, and its continuous forces will eventually wear down almost any surface or structure. Erosion can be caused or aggravated by improper drainage, settlement, pedestrian traffic, inadequate vegetation, animal burrows, or other factors. The cause of the erosion will have a direct bearing on the type of repair needed. Erosion in and around dams can lead to failure of a dam if left untreated. Periodic and timely maintenance is essential in preventing continuous deterioration and possible failure.

A sturdy sod, free of weeds and brush, is one of the most effective means of erosion protection. Embankment slopes are normally designed and constructed so that the surface drainage will be spread out in thin layers as "sheet flow" on the grassy cover. When the sod is in poor condition or flows are concentrated at one or more locations, the resulting erosion will leave rills and gullies in the embankment slope. The owner or inspector should look for these areas and be aware of the problems that may develop.

Prompt repair of vegetated areas that develop erosion is required to prevent more serious damage to the embankment. Rills and gullies should be filled with suitable soil (the upper 4 inches should be topsoil, if available), compacted, and then seeded. Erosion in large gullies can be slowed by stacking bales of hay or straw across the gully until permanent repairs can be made.

Figure 4-4 Erosion along the shoreline of an embankment dam.

Not only should the eroded areas be repaired, but the cause of the erosion should be addressed to prevent a continuing maintenance problem. Erosion might be aggravated by improper drainage, settlement, pedestrian traffic, animal burrows, or other forces. The cause of the erosion will have a direct bearing on the type of repair needed.

Paths from pedestrian and vehicle traffic are problems common to many embankments. If a path has become established, vegetation in this area will not provide adequate protection and more durable cover will be required, unless the traffic is eliminated. Small stones, asphalt, or concrete have been used effectively to cover footpaths. Embedding railroad ties or other treated wood beams into the upstream slope of the embankment to form steps is one of the most successful and inexpensive methods used to provide a protected pathway. Barriers should be constructed along paths used by motorcycles and off-road-vehicles to discourage their use on a dam.

Another area where erosion commonly occurs is the contact between the embankment and the concrete walls of the spillway or other structures. Poor compaction adjacent to the wall during construction and subsequent settlement could leave an area lower than the grade of the embankment. Runoff often concentrates along these structures, resulting in erosion. People frequently walk along these walls, wearing down the vegetal cover and compounding the problem. Possible solutions include grading the area to slope away from the wall and adding more resistant surface protection.

Adequate erosion protection is required along the contact between the downstream face of the embankment and the abutments. Runoff from rainfall concentrates in these gutter areas and can reach erosive velocities because of the steep slopes. Berms on the downstream face that collect surface water and empty into these gutters add to the runoff volume. Sod gutters may not adequately prevent erosion in these areas. Paved concrete gutters do not hold up well, will not slow the velocity of the water, can become undermined, and therefore are not recommended. Small animals often construct burrows underneath concrete gutters, possibly because burrowing is easier due to existing undermining. A well graded mixture of rock with stones 9 to 12 inches in diameter or larger placed on a sand filter generally provides the best protection in groins on small dams. Slush-grouted riprap (riprap filled with a thin concrete slurry) has also been successful in preventing erosion and can be used if large stone is not available or for groins of larger dams. A properly designed filter should be constructed beneath the slush grouted riprap.

As with erosion around spillways, erosion adjacent to gutters results from improper construction or a poor design in which the finished gutter is too high with respect to adjacent ground. This condition prevents much of the runoff water from entering the gutter. Instead, the flow concentrates along the side of the gutter, erodes and may eventually undermine the gutter. Care should be taken when replacing failed gutters or designing new gutters to assure that the channel has adequate capacity and erosion protection, a satisfactory filter, that surface runoff can easily enter the gutter, and that the outlet is adequately protected from erosion

A serious erosion problem which can develop on the upstream slope is "beaching." Waves caused by high winds or high-speed power boats can erode the exposed face of the embankment. Waves repeatedly strike the surface just above the pool elevation, rush up the slope, then tumble downward into the pool. This action erodes material from the face of the embankment and displaces it farther down the slope, creating a "beach". Erosion of unprotected soil can be rapid and during a severe storm could lead to complete failure of a dam. The upstream face of a dam is commonly protected against wave erosion and the resultant beaching by placement of a layer of rock riprap over a layer of filter material. In some cases other materials such as steel, bituminous or concrete facing, bricks or concrete blocks are used. Generally, rock riprap provides the most economical protection.

Beaching can also occur in existing riprap if the embankment surface is not properly protected by a filter. Water running down the slope under the riprap can erode the embankment. Sections of riprap slumped downward are often signs of beaching. Concrete facing used to protect slopes often fails because the wave action washes soil particles from beneath the slabs through joints and cracks. Detection, in this case, is difficult because the voids are hidden and failure may be sudden and extensive. Effective slope protection must prevent soil particles from being removed from the embankment.

When erosion occurs and beaching develops on the upstream slope of a dam, repairs should be made as soon as possible. The pool level should be lowered and the surface of the dam prepared for replacing the slope protection. A small berm or bench should be made across the face of the dam to help hold the protective layer in place. The bench should be placed at the base of the new layer of protection. The depth of the bench will depend on the thickness of the protection layer. The layer should extend a minimum of 3 feet below the lowest anticipated pool level. Otherwise, wave action during periods when the lake level is drawn down can undermine and destroy the protective layer. If rock riprap is used, it should consist of a heterogeneous mixture of irregular shapes placed over a sand and gravel filter. The maximum rock size and weight must be large enough to break up the energy of the maximum anticipated wave action and hold the small stones in place. Generally, the largest stones should be at least 12-24 inches in diameter. The smaller rocks help to fill the spaces between the larger pieces forming a resistant mass. The filter prevents soil particles on the embankment surface from being washed out through the spaces (or voids) between the rocks in the riprap. If the filter material can be washed out through these voids and beaching develops, two filter layers will be required. The lower layer should be composed of sand or filter fabric to protect the soil surface. The upper layer should be composed of coarser materials that prevent washout through the voids in the riprap.

The soil selected for repairing erosion should be free from vegetation, organic materials, trash, or large rock. Most of the soil should be fine-grained, cohesive soils which easily break down when worked with compaction equipment. The intent is to use a material which, when compacted, forms a firm, solid mass, free from excessive voids. The upper 4 to 6 inches should be topsoil capable of supporting vegetative growth.

If flow-resistant portions of an embankment are being repaired, materials which are high in clay or silt content should be used. If the area is to be free draining or highly permeable (i.e., riprap bedding, etc.) the material should have a higher percentage of sand and gravel. As a general rule, it is usually satisfactory to replace or repair damaged areas with soils similar to those originally in place.

An important soil property affecting compaction is moisture content. Soils which are too dry or too wet do not compact well. One may roughly test repair material by squeezing it into a tight ball. If the sample maintains its shape without cracking and falling apart (which means it is too dry), and without depositing excess water onto the hand (which means it is too wet), the moisture content is probably near the proper level.

Before placement of soil, the repair area must be prepared by removing all inappropriate material. Vegetation such as brush, roots, and tree stumps must be cleared and any large rocks or trash removed. Also, unsuitable earth, such as organic or loose soils, should be removed, so that the work surface consists of exposed firm clean embankment material. Following clean-up, the affected area should be shaped and dressed, so that the new fill can be compacted and will properly tie into the existing fill. If possible, slopes should be trimmed, and surfaces roughened by scarifying or plowing to improve the bond between the new and existing fill and to provide a good base to compact against.

Soils should be placed in loose layers up to 12 inches thick and compacted manually or mechanically to form a dense mass free from large rock or organic material. Compacted soil layers should not exceed 6 to 9 inches. Soil moisture must be maintained in the proper range. The fill should be watered and mixed to the proper wetness or scarified and allowed to dry if too wet. During backfilling, care should be taken so that the fill soil does not become too wet from rainstorm runoff. Runoff should be directed away from the work area and repair areas should be overfilled so that the fill maintains a crown which will shed water.

Preventive maintenance to help prevent erosion includes the following:

- Periodic mowing to prevent trees, brush, and weeds from becoming established, and to encourage the growth of grass. Poor vegetative cover will usually result in extensive and rapid erosion.
- Timely repair of erosion damage, particularly after high flows. Erosion can be expected in spillway channels during high flows and can also occur as a result of rainfall and local runoff. Local runoff is more significant in large spillways and may require special treatment, such as terraces or drainage channels. Erosion of the channel slopes deposits material in the spillway channel, especially where the slopes meet the channel bottom. In small spillways, this can significantly reduce the spillway capacity. This condition often occurs immediately after construction, before vegetation becomes established. In these cases, it may be necessary to reshape the channel to provide the necessary capacity.
- Seeding and fertilization as necessary to maintain a vigorous growth of vegetation. Fescue provides excellent erosion protection, but may require approval from IDNR before using it.
- Installation of erosion control fabrics.
- Use of straw/hay bales, or rock checks in swales where water concentrates.
- Post signage to prohibit pedestrian and vehicular access to sensitive areas.
- Prohibit fishing from the embankment.

4.4 SEEPAGE

All dams, regardless of type, have seepage in one form or another. Seepage may be through the foundation, through the embankment, or along the foundation-embankment interface. The seepage volumes may be substantial or barely noticeable. The water may be transporting suspended or dissolved solids. In some cases, the seepage may be entirely harmless; in others, it may be extremely serious and immediate treatment becomes imperative.

Figure 4-5 Seepage at this embankment dam is collected in a rock drain and discharged through a PVC pipe. This drain was recently installed as evidenced by the fresh soil fill.

Seepage can emerge anywhere on the downstream face of the dam, beyond the toe, or on the downstream abutments at elevations below normal pool. Seepage may vary in appearance from a "soft", wet area to a flowing channel of water. It may show up first as only an area where the vegetation is more lush and darker green. Cattails, reeds, mosses, and other marsh vegetation often become established in a seepage area. Downstream groin areas (the areas where the downstream face contacts the abutments) are prime areas for seepage. Seepage can also occur along the contact between the embankment and a conduit spillway, drain, or other appurtenance. Slides in the embankment or an abutment may be the result of seepage causing soil saturation or loss of soil strength. At most dams, some water will seep from the reservoir through the foundation. Where it is not intercepted by a subsurface drain, the seepage will emerge downstream from or at the toe of the embankment. If the seepage forces are large enough, soil will be eroded from the foundation and be deposited in the shape of a cone around the outlet. If these "boils" appear, professional advice should be sought immediately. Seepage flow which is muddy and carrying soil particles may be evidence of "piping," and complete failure could occur within hours. Piping can occur along a spillway and other conduits through the embankment, and these areas should be closely inspected. Sinkholes that develop on the embankment above buried conduits are signs that piping has begun and a professional engineer should immediately be retained to investigate the situation. If the extent of piping is large enough, rapid and complete failure of the dam could be imminent. Emergency procedures, including downstream evacuation, must be implemented if this condition is noted.

The need for seepage control will depend on the quantity, content, and location of the seepage. Other factors to be considered when evaluating seepage problems include the seepage path and pattern, configuration of the dam, and the engineering properties of the embankment materials. Controlling the quantity of seepage that occurs after construction is difficult, quite expensive, and not usually attempted unless drawdown of the pool level has occurred or the seepage is endangering the embankment or appurtenant structures. Typical methods used to control the quantity of seepage are grouting, installation of an upstream blanket, or slurry walls. Relief wells can be installed to relieve the water pressure in the foundation. Grouting is most applicable to leakage zones in bedrock, abutments, and foundations. Extreme care should be exercised when grouting in fill material. All these methods must be designed and constructed under the supervision of a professional engineer experienced with dams.

Controlling the content of the seepage or preventing seepage flow from removing soil particles is extremely important. Modern design practice incorporates this control into the embankment through the use of cutoffs, internal filters, and adequate drainage provisions. Control at points of seepage exit can be accomplished after construction by using weighted filters, drain pipes, trench drains, and other methods of drainage. The filter and drainage system should be designed to prevent migration of soil particles and still provide for passage of the seepage flow. Geotextiles or synthetic fabrics have worked quite well as filters in many applications; and should be considered by the engineer and the owner as a means of controlling seepage.

The bottom layer of the weighted filter should include 6 to 12 inches of sand placed over the seepage area. A properly designed geotextile should be placed beneath the sand or the gradation of the sand should be based on the particle sizes of the foundation or fill material. The sand layer should be covered with a gravel layer of similar thickness. Larger rock should be placed next, to complete the weighted filter (when placed above the ground surface, shape to form a berm). This method will permit the seepage to drain freely, but prevent piping (removal) of soil particles. The weight of the berm will hold the filter in place and may also provide additional stability to the embankment and foundation.

The location of the seepage or wet area on the embankment or abutment is often a primary concern. Excessive seepage pressure or soil saturation can threaten the stability of the downstream slope of the dam or the abutment slopes. An abutment slide might block or damage the spillway outlet or other appurtenances. In these cases, not only must the seepage be controlled but the area must be dried out. This is sometimes accomplished by installing finger drains (lateral trench drains for specific locations). Seepage control systems must always be free-draining to be effective.

Regular monitoring is essential to detect seepage and prevent failure. Without knowledge of the dam's history, the owner or the inspector has no idea whether the seepage condition is in a steady or changing state. It is important to keep written records of points of seepage exit, quantity and content of flow, size of wet area, and type of vegetation for later comparison. Photographs provide invaluable records of seepage. The inspector should always look for increases in flow and evidence of flow carrying soil particles. The control methods described previously are often designed to facilitate observation of flows. It is highly recommended that a v-notch weir be included in the design of a filter and drain system to measure the flow rates.

Regular surveillance and maintenance of internal embankment and foundation drainage outlets is also required. Normal maintenance consists of removing any soil or other material that obstructs flow. Internal repair is complicated and often impractical and should not be attempted without professional advice. The rate and content of flow emerging from these outlets should be monitored regularly.

4.5 EMBANKMENT STRUCTURE

The dam embankment and any appurtenant dikes must safely contain the reservoir. Cracks, slides, sloughing, and settlement are signs of embankment distress and indicate that maintenance or remedial work is required. The cause of the distress should be determined by a qualified dam safety professional before undertaking repairs on dams. This step is important because a so-called "home remedy" may cause greater and more serious damage to the embankment and may eventually result in unwise expenditures for useless repairs.

The entire embankment should be closely inspected for cracks. Short, isolated cracks are not usually significant, but larger (wider than 1 or 2 inches), well-defined cracks may indicate a more serious problem. There are three types of cracks: transverse, longitudinal, and diagonal. Transverse cracks appear across the embankment and indicate differential settlement within the embankment. Such cracks provide avenues for seepage water and piping could develop quickly. Longitudinal cracks run parallel to the embankment and may signal the early stages of a slide on either face of the embankment. In recently built structures, these cracks may indicate inadequate compaction of the embankment during construction. Diagonal cracks are intermediate vertical cracks that form in the embankment as a result of slides or differential settlement.

Small cracks, as they appear, should be documented, examined by an engineer, and then sealed. The seal will prevent surface water from entering the cracks, causing saturation of embankment material, and possibly triggering a slide or other serious problem. Sealing can be accomplished by compacting cohesive soil in the cracks. Unless the cracks are large (wider than an inch), this can usually be done in a few minutes using a shovel and a compacting tool. After the cracks have been sealed, the areas should be monitored frequently to determine if movement is still occurring.

Slides or crack locations should be documented by staking and photographs. Continued movement is an indication of a more serious problem such as a slide. Slides and sloughs are serious threats to the safety of a dam. A massive slide can initiate catastrophic failure of a dam. Slides can be detected easily unless obscured by tall vegetation. Arc-shaped cracks are indications that a slide or slough is beginning. These cracks soon develop into a large scarp in the slope at the top of the slide. If a slide develops, the scarp should be sealed to prevent rainfall and surface runoff from lubricating the interior slide surface, saturating the embankment, and causing future sliding. Sealing the scarp is only a temporary measure. The need for immediate professional assistance to determine the cause of cracks and slides and to recommend remedial action cannot be overemphasized.

Occasionally minor cracks will form in an earth dam because of surface drying. These are called desiccation (drying) cracks and should not be confused with structural or settlement cracks. Drying cracks are usually parallel to the main axis of the dam, typically near the upstream or downstream shoulders of the crest. These cracks often run intermittently along the length of the dam and may be up to 4 feet deep. Drying cracks can be distinguished from more serious structural cracks because the former are usually no wider than a few inches and have edges that are not offset vertically. As a precaution, suspected drying cracks should initially be monitored with the same care used for structural cracks. The problem area should be marked with survey stakes, and monitoring pins should be installed on either side of the crack to allow recording of any changes in width or vertical offset. Once satisfied that observed cracking is the result of shrinkage or drying, an owner may stop monitoring. These cracks will often close as climatic or soil moisture conditions change. If they do not, it may be necessary to backfill the cracks to prevent entry of surface moisture which could result in saturation of the dam. The cracks may be simply filled with cohesive soil that is tamped in place with hand tools. It is also recommended that the crest of a dam be graded to direct runoff waters away from areas damaged by drying cracks.

Slide debris in spillway and outlet areas should be removed immediately, because the debris reduces hydraulic capacities. Shallow surface slides can be repaired by removing the slide material and rebuilding the slope to original grade with well compacted impervious, cohesive soil material. The cause for any slide should be fully determined before implementing permanent repairs to the slope.

Settlement occurs both during construction and after the embankment has been completed and placed in service. To a certain degree, this is normal and should be expected. Settlement is usually most pronounced at locations of maximum foundation depth or embankment height. Excessive settlement will reduce the freeboard (the difference in elevation between the water surface and the top of the dam) and may increase the probability of overtopping. Any areas of excessive settlement should be restored to original elevations and conditions to reduce the risk of overtopping. A relatively large amount of settlement (more than one foot) within a small area could indicate serious problems in the foundation or perhaps in the lower part of the embankment. Settlement accompanied by cracking often precedes failure. When either condition is observed, professional advice should be sought. Settlement can be monitored by measuring the differences in elevation between the problem area and permanent reference monuments located away from the dam. Land surveying instruments are required to make these measurements.

Repair of cracks, slides, and settlement in dams usually requires the removal of all unsuitable material and the addition of good material to the embankment. Filters and drains may also be necessary to correct these problems. Soil added to restore an embankment should be properly "keyed" into the base material. This can best be accomplished by removing the vegetal cover and all unsuitable material until a good, firm base in undisturbed soil is uncovered. Unsuitable materials include wet, soft; porous, organic, and improperly compacted soils. The surface should then be roughened with a disc or similar device to obtain a good bond between "old" and "new" materials. The new soil should be successively compacted in thin layers (6 to 9 inches thick) before adding more material. Compaction of each layer to at least 95 percent maximum dry density at 1 percentage point below to 3 percentage points above optimum moisture content based on the Standard Proctor density test (ASTM D698) is recommended for cohesive soils used in dams.

Soils used for repair of embankment problems should be the same as that as described earlier in Subchapter 4.3, Erosion.

4.6 SPILLWAYS

Many dams have pipes (or conduits) that serve as principal spillways. These conduits are required to carry normal stream and small flood flows safely past the embankment throughout the life of the structure. Pipes through embankments are difficult to construct properly, can be extremely dangerous to the embankment if problems develop after construction, and are usually difficult to repair because of their location and size.

Maximum attention should be directed to maintaining these structures. The use of pipe whose joints are not designed to handle pressure flows, such as corrugated metal pipe, should be avoided when replacing or repairing existing pipe. The joints in a pipe can be affected by differential settlement of the embankment, bedding failure, positive and negative pressures within the pipe, and slides and seepage through the embankment. Therefore, it is imperative that pipe with pressure tight joints that can withstand minor deflections be used in a dam.

Frequent inspection is necessary to ensure the spillway conduit is functioning properly. All conduits should be inspected thoroughly once a year. Conduits which are 30 inches or more in diameter can be entered and visually inspected. The conduits should be inspected for improper alignment (sagging), separation and displacement at joints, cracks, leaks, surface wear, loss of protective coatings, corrosion, and blockage.

Figure 4-6 This corrugated metal pipe is completely rusted through on the bottom, creating a safety concern. Metal pipes are not recommended for use in dams.

Problems with conduits occur most often at joints, and special attention should be given them during the inspection. The joints should be checked for gaps caused by elongation or settlement and loss of joint-filler material. Open joints can permit erosion of embankment material or cause leakage of water into the embankment during pressure flow. The outlet should be checked for signs of water seeping along the exterior surface of the pipe. A depression in the soil surface over the pipe may be a sign that soil is being removed from around the pipe.

Effective repair of the internal surface or joint of a conduit is difficult and should not be attempted without careful planning and proper professional supervision. Listed below are comments regarding pipe repairs.

- Asphalt mastic used as joint filler becomes hard and brittle, is easily eroded, and will generally provide a satisfactory seal for only about five years. Mastic should not be used if the pipe is expected to flow under pressure. For these reasons asphalt mastic is not recommended for other than temporary repairs.
- The instructions on the label should be followed when using thermosetting plastics (epoxy). Most of these products must be applied to a very clean and dry surface to establish an effective bond.
- Material used as joint filler should be impervious to water and should be flexible throughout the range of expected air and water temperatures.
- The internal surfaces of the conduit should be made as smooth as possible when

repairs are made so that high-velocity flow will not damage the repair material.
- Hairline cracks in concrete are not generally considered a dangerous problem and repair is not needed unless the cracks open up or transmit water.

A common problem with pipe spillways and other conduits made of metal is corrosion. Exposure to moisture, acid conditions, or salt will accelerate the corrosion process. Acid runoff from strip-mine areas will cause rapid corrosion of metal pipes. Metal pipes are available which have been coated to resist accelerated corrosion. Coatings can be of epoxy, aluminum, or zinc (galvanized). Coatings applied to pipes in service are generally not very effective because of the difficulty in establishing a bond. Bituminous coatings cannot be expected to last more than one or two years on flow ways. Corrosion can be controlled or arrested by installing cathodic protection. A metallic anode such as magnesium is buried in the soil and is connected to the metal pipe by wire. Natural voltage causes current to flow from the magnesium (anode) to the pipe (cathode) and will cause the magnesium to corrode and not the pipe. Corrosion shortens the life of metal pipes through dams. The corrosion rate is dependant upon the soil PH, water content, metal thickness, and overburden load. All metal pipes need to be closely monitored with respect to operation of the pipe. Metal pipes are not recommended and should be upgraded to concrete when repairs are required.

Corrosion of metal parts of operating mechanisms can be effectively treated and prevented by keeping these parts oiled and/or painted.

Figure 4-7 Erosion at the outlet of a principal spillway discharge pipe. Note that the pipe is plastic, which is not recommended for use as a principal spillway structure.

Erosion at the spillway outlet, whether it be a pipe or overflow spillway, is one of the most common spillway problems encountered. Severe undermining of the outlet can displace sections of pipe, cause slides in the downstream slope of the dam as erosion continues, and eventually lead to complete failure of a dam. Water must be conveyed safely from the lake to a point downstream of the dam without endangering the spillway or embankment. Often the spillway outlet is adequately protected for normal flow conditions, but not for extreme flows. It is easy to underestimate the energy and force of flowing water or overestimate the resistance of the outlet material (earth, rock, concrete, etc). The required level of protection is hard to establish by visual inspection but can usually be determined by hydraulic calculations performed by a professional engineer.

Structures that provide complete erosion control at a spillway outlet are usually expensive to construct, but often necessary. Less expensive types of protection can be effective, but require more extensive periodic maintenance. As areas of erosion and deterioration develop, repairs must be promptly initiated. To properly correct the problem, the cause of the damage must be determined. The following four factors, often interrelated, contribute to erosion at the spillway outlet.

1) Flows emerging from the outlet are normally at an elevation above the stream channel. If the outlet flows emerge at the correct elevation, tailwater in the stream channel can absorb a substantial amount of the high velocity flow.
2) Flows emerging from the spillway are generally free of sediment and therefore have substantial sediment-carrying capacity. In obtaining the appropriate sediment load, the moving water will scour soil material from the channel and leave eroded areas. Such erosion is difficult to estimate and requires that the outlet be protected for a safe distance downstream from the dam.
3) Flows leaving the outlet at high velocity can create negative pressures that can cause material to be loosened and removed from the floor and walls of the outlet channel. This action is known as "cavitation" and can affect concrete or metal surfaces. Venting can sometimes be used to relieve negative pressures; however, the size and location of a vent should be determined by a professional engineer.
4) Water leaking through pipe joints or flowing along a pipe from the reservoir may weaken the soil structure around the pipe. Inadequate compaction adjacent to the structure during construction and the absence of sand diaphragms will compound the problem.

Figure 4-8 Erosion of fill behind this wall at the outlet of the principal spillway was caused by water splashing over the wall during a large storm event. Larger rock or concrete will be required to prevent this from happening again.

Eroded and undermined areas at spillway outlets can sometimes be repaired by filling these areas with large stone. Stone that is large enough to be effective needs to weigh in excess of 500 pounds (18 to 24 inches in diameter). Often stones this size are not available or are expensive to buy and haul. Owners should be aware that placing large stones in the undermined areas adjacent to spillway outlets may not solve a problem. Often these eroded areas are a result of a more serious problem with the dam. Gabions have been used successfully in areas where the velocity is low but should not be used where high velocity and turbulence are expected. Gabions require careful foundation preparation and experienced personnel for Installation. Properly designed plunge pools are acceptable but can require frequent maintenance. In many cases, professional help should be sought for complete redesign and construction of the outlet.

The function of an emergency spillway is to convey flood flows past the dam in a manner that will ensure that the dam is not overtopped. Vegetated-earth, rock, and concrete spillways are commonly used as an economical means to provide emergency spillway capacity. Normal flows are carried by the principal spillway, and infrequent, large flood flows pass primarily through the emergency spillway. For dams with pipe conduit spillways, an emergency spillway is almost always required as a back-up in case the pipe becomes plugged. These spillways are often neglected because the owner rarely, if ever, sees them flow. Emergency spillways usually are designed to flow only once every 25 to 100 years or more; however, maintenance is still very important.

Maintenance of vegetated-earth spillways is covered under earlier Subchapters 4.2 and 4.3. Additionally obstructions in the spillways should be removed immediately after their discovery.

Emergency spillways often are used for purposes other than passage of flood flows. Among these uses are reservoir access, parking lots, boat ramps, boat storage, pasture, and cropland. Permanent structures (buildings, fences, etc.) should not be constructed in emergency spillways. If fences are absolutely necessary, they should cross the spillway far enough away from the crest (control section) so they do not interfere with flow. After flows occur, the fences should be cleared of all debris, trees, and brush.

Maintenance of rock spillways should include the periodic removal of trees, brush, and debris from flood flows and rock slides. Rock slides can be a major problem in areas where open channel spillways have been cut into weathered or highly fractured rock. Large rock that has fallen into the channel can partially block an emergency spillway and reduce its discharge capacity. Rock spillways should be inspected frequently and cleaned out whenever debris accumulates in the channel. Erosion of rock spillways is not normally a problem; however, many spillways are constructed adjacent to the dam and founded partially in rock and partially in natural soil or fill material. In these cases, a training berm is required to direct flows away from the dam. This berm and the channel side next to the dam should be inspected for erosion whenever the spillway is used. Erosion protection consisting of riprap or concrete and designed to hold up under the velocities expected during the spillway design flood should be provided and maintained.

Figure 4-9 The floor and side walls of this concrete spillway are badly deteriorated and in need of repair.

Maintenance of concrete spillways should include keeping the channel clear of debris, filling joints and cracks, keeping underdrains open and maintaining the structural stability of the concrete. Concrete spillways must be inspected for cracks or displacements caused by settlement, foundation failure, uncontrolled seepage, and frost action. Voids created by the settlement of compressible soils beneath spillways and uncontrolled seepage may cause the concrete to crack or displace due to lack of support. When temperatures fall below the freezing point, water located in the soil voids begins to freeze. Ice lenses can form and cause the concrete to crack and displace by a mechanism known as "frost heave." It is important to provide adequate drainage for concrete located on soil. Drains under concrete must be kept clear. Clogged or plugged drains, and inadequate filter systems can cause saturated conditions beneath the concrete. More information on concrete rehabilitation and seepage is contained in the subchapter on Concrete Repair.

4.7 TRASH RACKS

Many dams in Indiana have pipe and riser spillways. Pipe spillway inlets that become plugged with debris or trash reduce spillway capacity. As a result, the potential for overtopping the dam is greatly increased, particularly if there is only one spillway. If the dam has an emergency spillway channel, a plugged principal spillway will cause more frequent and greater flow in the emergency spillway. Because emergency spillways are generally designed for infrequent flows of short duration, serious damage will likely result from greater flows. For these reasons, trash racks or collectors must be installed at the inlets to pipe spillways and lake drains. If no trash rack is present, one should be installed immediately.

Figure 4-10 This is an example of a bad trash rack design. Trash racks should not be designed or constructed to be one-dimensional (flat, flush with water surface); this design almost guarantees clogging.

A well-designed trash rack will stop large debris that could plug the pipe but allow unrestricted passage of water and smaller debris. Some of the most effective trash racks allow flow to pass beneath the trash rack into the riser inlet as the pool level rises. Trash racks usually become plugged because the openings are too small or the head loss at the rack causes material and sediment to settle and accumulate. Small openings will stop small debris such as twigs and leaves, which in turn cause a progression of larger items to build up, eventually blocking the inlet. Trash rack openings should be at least 6 inches across regardless of the pipe size. The larger the principal spillway conduit, the larger the trash rack opening should be. The largest possible openings should be used, up to a maximum of about 12 inches.

The trash rack should be properly attached to the riser inlet and strong enough to withstand the hammering forces of debris being carried by high-velocity flow, a heavy load of debris, and ice. If the riser is readily accessible, vandals will throw riprap and debris into it. To prevent such vandalism, the size of the trash rack openings should not be decreased, but rock that is larger than the openings, too large to handle, or covered with concrete slurry should be used. Maintenance should include periodic inspections for rusted and broken sections and repairs made as needed. The trash rack should be checked frequently during and after storms to ensure it is functioning properly and to remove accumulated debris.

4.8 RIPRAP

A dam owner should expect some deterioration (weathering) and displacement of riprap. Freezing and thawing, wetting and drying, abrasive wave action, and other natural processes will eventually break down or remove the riprap. Its useful life varies with the characteristics of the stone used. Stone for riprap should be rock that is dense and well cemented. Due to the high initial cost of rock riprap, its durability should be determined by appropriate testing procedures prior to installation.

A serious erosion problem called "beaching" can develop on the upstream slope of a dam as discussed earlier. The upstream face of a dam is commonly protected against wave erosion and resultant beaching by placement on the face of a layer of rock riprap over a layer of filter material. Sometimes, materials such as steel, bituminous or concrete facing, bricks, or concrete blocks are used for this upstream slope protection. Protective beaches are sometimes actually built into small dams by placing a berm (8 to 10 feet wide) along the upstream face a short distance below the normal pool level thereby providing a surface on which wave energy can dissipate. Generally, however, rock riprap provides the most economical and effective protection.


Figure 4-11 Embankment dam exhibiting minor shoreline erosion.

Nonetheless, beaching can occur in existing riprap if the embankment surface is not properly protected by a filter. Sections of riprap which have slumped downward are often signs of this kind of beaching. Similarly, concrete facing used to protect slopes may fail because waves wash soil from beneath the slabs through joints and cracks. Detection of this problem is difficult because the voids are hidden and failure may be sudden and extensive. Effective slope protection must prevent soil from being removed from the embankment.

When erosion occurs and beaching develops on the upstream slope of a dam, repairs should be made as soon as possible. The pool level should be lowered and the surface of the dam prepared for repair. A small berm or "bench" should be built across the face of the dam at the base of the new layer of protection to help hold the layer in place. The size of the bench needed depends on the thickness of the protective layer. The riprap layer should extend a minimum of 3 feet below the lowest expected normal pool level. See Subchapter 4.3 for a description of riprap placement repair.

The useful life of riprap varies depending on the characteristics of the stone used. Thus, stone for riprap should be rock that is dense and well cemented. When riprap breaks down, and erosion and beaching occur more often than once every three to five years, professional advice should be sought to design more effective slope protection.

4.9 CONCRETE REPAIR

This subchapter presents a brief overview of concrete repair methods, obtained from the U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center *Guide to Concrete Repair*, 1997; U.S. Government Printing Office, Washington, D.C. 20402-9328.

Concrete is an inexpensive, durable, strong, basic building material often used in dams for core walls, spillways, stilling basins, control towers, and slope protection. However, forces of nature and poor design, workmanship, construction procedures, and materials may cause imperfections that later require repair. Long term deterioration or damage caused by flowing water, ice, or other natural forces must be corrected.

Concrete surfaces should be examined for spalling and deterioration due to weathering, unusual or extreme stresses, alkali or other chemical action, erosion, cavitation, vandalism, and other destructive forces (see Part 3).

Structural problems are indicated by cracking, exposed reinforcing bars, large areas of broken-out concrete, misalignment at joints, undermining, and settlement. Rust stains may indicate internal rusting and deterioration of reinforcement steel. Spillway floor slabs and upstream-slope protection slabs should be checked for undermining (erosion of base materials). Concrete wall and tower structures should be examined for settlement and their alignment checked. Concrete surfaces adjacent to contraction joints and subject to flowing water are of special concern. The adjacent surfaces must be flush or the downstream edge slightly lower to prevent erosion of the concrete and to prevent water from being directed into the joint during high velocity flow. All joints should be kept free of vegetation. All weep holes should be checked for blockage, and stain outlines on concrete surfaces studied for indications of flow characteristics.

Floor or wall movement, extensive cracking, improper alignments, settlement, joint displacement, and extensive undermining are signs of major structural problems. Drainage systems may be needed to relieve excessive water pressures under floors and behind walls. Because of their complex nature, major structural repairs require professional advice and are not addressed here.

The United States Department of the Interior, Bureau of Reclamation has developed a seven-step repair system for concrete that is an excellent procedure. The Bureau of Reclamation has developed, used, and evaluated this procedure over an extended period of time, and has found it to be suitable for repairing construction defects in newly constructed concrete as well as old concrete that has been damaged by long exposure and service under field conditions. The methodology is presented in their manual, “Guide to Concrete Repair,” April 1997, Technical Service Center; it is for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington D.C. 20402.

The repair system will be found most useful if followed in a numerically sequential or step-wise manner. Quite often, the first questions asked about deteriorated or damaged concrete are: "What should be used to repair this?" and "How much is this going to cost?" These are not improper questions, however, they are questions asked at an improper time. Ultimately, these questions must be answered, but pursuing answers to these questions too early in the repair process may lead to incorrect and, therefore, extremely costly solutions. If a systematic approach to repair is used, such questions will be asked when sufficient information has been developed to provide correct and economical answers.

The Bureau of Reclamation’s seven step repair system is as follows:

1. Determine the cause(s) of damage
2. Evaluate the extent of damage
3. Evaluate the need to repair
4. Select the repair method
5. Prepare the old concrete for repair
6. Apply the repair method
7. Cure the repair properly


Figure 4-12 A large reflective crack has formed in a concrete overlay which also exhibits circular drying shrinkage cracking.

1. Determine the Cause(s) of Damage

The first and often most important step of repairing damaged or deteriorated concrete is to correctly determine the cause of the damage. If the cause of the original damage to concrete is not determined and eliminated, or if an incorrect determination is made, whatever damaged the original concrete will likely also damage the repaired concrete. Money and effort spent for such repairs is, thus, totally wasted. Additionally, larger and even more costly replacement repairs will then be required.

Figure 4-13 Absorptive aggregate popout on spillway floor.

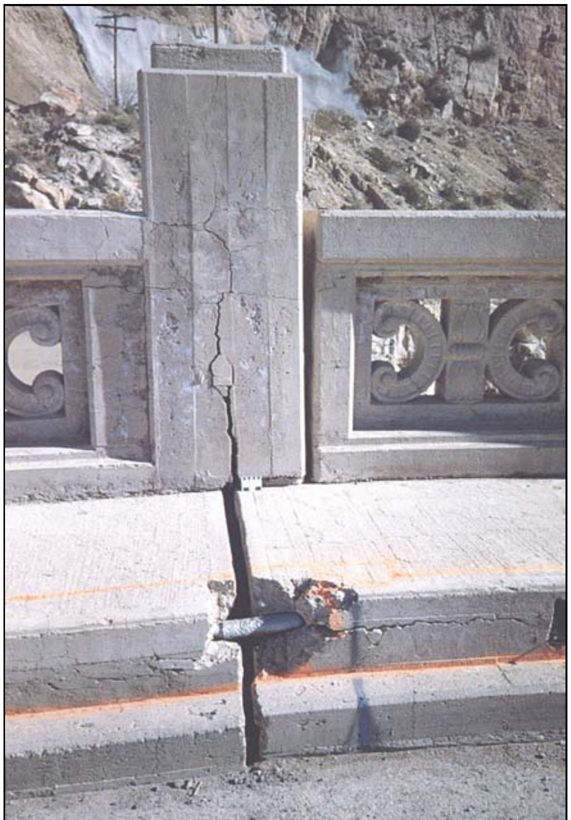

Figure 4-14 Multiple causes of damage are apparent in this photograph. Poor design or construction practices placed the electrical conduit too near the surface. A combination of freezing and thawing deterioration and alkali-aggregate reaction is responsible for the cracking and surface spalling on the parapet wall.

If the original damage is the result of a one-time event, such as a river barge hitting a bridge pier, an earthquake, or structural overload, remediation of the cause of damage need not be addressed. It is unlikely that such an event will occur again. If, however, the cause of damage is of a continuing or recurring nature, remediation must be addressed, or the repair method and materials must in some manner be made resistant to predictable future damage. A quick review of common causes of damage usually reveals that the majority of them are of a continuing or recurring nature.

It is important to differentiate between causes of damage and symptoms of damage. In the above case of the river barge hitting the bridge pier, the cause of damage is the impact to the concrete. The resultant cracking is a symptom of that impact. In the event of freezing and thawing deterioration to modem concrete, the cause of the damage may well lie with the use of low quality or dirty fine or coarse aggregate in the concrete mixture or the lack of entrained air. The resultant scaling and cracking is a symptom of low durability concrete. The application of high cost repairs to low quality concrete is usually economically questionable. Cavitation damage occurs when high velocity water flows encounter discontinuities on the flow surface. Thus, cavitation is just a symptom of the problem.

It is somewhat common to find that multiple causes of damage exist. Improper design, low quality materials, or poor construction practices reduce the durability of concrete and increase its susceptibility to deterioration from other causes. Similarly, sulfate and alkali-silica deterioration cause cracks in the exterior surfaces of concrete that allow accelerated deterioration from cycles of freezing and thawing. The deterioration resulting from the lowered resistance to cyclic freezing and thawing might mask the original cause of the damage.

Finally, it is important to fully understand the original design intent and concepts of a damaged structure before attempting repair. Low quality local aggregate may have

Figure 4-15 Severe cracking caused by alkali-aggregate reaction.

intentionally been used in the concrete mix because the costs associated with hauling higher quality aggregate great distances may have made it more economical to repair the structure when required at some future date. A classic example of misunderstanding the intent of design recently occurred on a project in Nebraska. A concrete sluiceway that would experience great quantities of waterborne sand was designed with an abrasion-resistant protective overlay of silica fume concrete. This overlay was intentionally designed so that it would not bond to the base concrete, making replacement easier when required by the anticipated abrasion-erosion damage. This design concept, however, was not communicated to construction personnel who became deeply concerned when the silica fume overlay was found to be "disbonded" shortly after placement and curing was completed. Some difficulty was experienced in preventing field personnel from requiring the construction contractor to repair a perfectly serviceable overlay that was performing exactly as intended.

2. Evaluate the Extent of Damage

The next step of the repair process is to evaluate the extent and severity of damage. The intent of this step is to determine how much concrete has been damaged and how this damage will affect serviceability of the structure (how long, how wide, how deep, and how much of the structure is involved). This activity includes prediction of how quickly the damage is occurring and what progression of the damage is likely.

The importance of determining the severity of the damage should be understood. Damage resulting from cyclic freezing and thawing, sulfate exposure, and alkali-aggregate reaction appears quite similar. The damage caused by alkali-aggregate reaction and sulfates is far more severe than that caused by freeze-thaw, although all three of these causes can result in destruction of the concrete and loss of the affected structure. The main difference in severity lies in the fact that proper maintenance can reduce damage caused by freeze-thaw. There is no proven method of reducing damage caused by alkali-aggregate reaction or sulfate exposure.

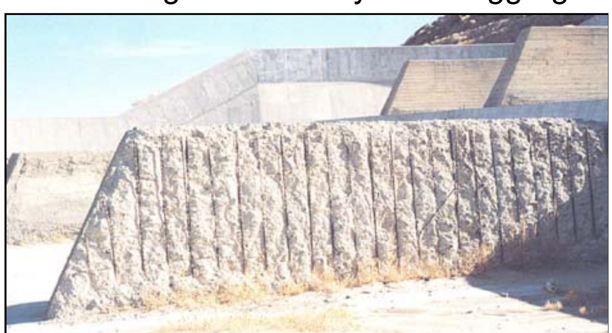

Figure 4-16 This freezing and thawing deterioration should have been repaired before it advanced to the point that wall replacement or removal is the only option.

The most common technique used to determine the extent of damage is sounding the damaged and surrounding undamaged concrete with a hammer. If performed by experienced personnel, this simple technique, when combined with a close visual inspection, will provide the needed information in many instances of concrete damage.

In sounding suspected delaminated or disbonded concrete, it should be remembered that deep delaminations or delaminations that contain only minute separation may not always sound drummy, or hollow. The presence of such delaminations can be detected by placing a hand close to the location of hammer blows or by closely observing sand particles on the surface close to the hammer blows. If the hand feels vibration in the concrete, or if the sand particles are seen to bounce however slightly due to the hammer blows, the concrete is delaminated.

An indication of the strength of concrete can also be determined by hammer blows. High strength concrete develops a distinct ring from a hammer blow and the hammer rebounds smartly. Low strength concrete resounds with a dull thud and little rebound of the hammer. More detailed information can be obtained by using commercially available rebound hammers, such as the Schmidt Rebound Hammer.


Figure 4-17 Gel resulting from alkali-aggregate reaction causes expansion and tension cracks in a concrete core.

Cores taken from the damaged areas can be used to detect subsurface deterioration, to determine strength properties through laboratory testing, and to determine petrography. Petrographic examination of concrete obtained by coring can also be very useful in determining most causes of deterioration.

There are a number of nondestructive testing methods that can be used to evaluate the extent of damage (Poston et al., 1995). The above-mentioned Schmidt Rebound Hammer is perhaps the cheapest and simplest to use. Ultrasonic pulse velocity and acoustic pulse echo devices measure the time required for an electronically generated sound wave to either travel through a concrete section or to travel to the far side of a concrete section and rebound. Damaged or low quality concrete deflects or attenuates such sound waves and can be detected by comparison of the resulting travel time with that of sound concrete. Acoustic emission devices detect the elastic waves that are generated when materials ate stressed or strained beyond their elastic limits. With such devices, it is possible to "hear" the impulses from development of microcracks in overly stressed concrete. Acoustic emission equipment has been used to "hear" the occurrence of prestressing strand failure in large diameter prestressed concrete pipe.

With computer assistance, several acoustic emission devices have been used not only to detect the occurrence of strand failure(s), but through triangulation, they were able to determine the location of the failure(s) (Travers, 1994).

The areas of deteriorated or damaged concrete discovered by these methods should be mapped or marked on drawings of the affected structure to provide information needed in subsequent calculations of the area and volume of concrete to be repaired and for preparation of repair specifications. Even though care is taken in these investigations, it is common to find during preparation of the concrete for repair that the actual area and volume of deteriorated concrete exceeds the original estimate. For this reason, it is usually a good idea to increase the computed quantity estimates by 15 to 25 percent to cover anticipated overruns.

3. Evaluate the Need to Repair


Figure 4-18 Spillway damage requiring repairs at some future date.

Not all damaged concrete requires immediate repair. Many factors need consideration before the decision to perform repairs can be made. Obviously, repair is required if the damage affects the safety or safe operation of the structure. Similarly, repairs should be performed if the deterioration has reached a state, or is progressing at a rate, such that future serviceability of the structure will be reduced. Most concrete damage, however, progresses slowly, and several options are usually available if the deterioration is detected early. With early detection, it may be possible to arrest the rate of deterioration using maintenance procedures. Even if repair is required, early detection of damage will allow orderly budgeting of funds to pay the costs of repair.

Some types of concrete deterioration can simply be ignored. Cracking due to drying shrinkage and freezing and thawing deterioration is common on the downstream face of many older western dams. These types of damage are unsightly, but repair can seldom be justified for other than cosmetic purposes. It should be anticipated that such repairs might be more unsightly and of lower durability than the existing concrete. Conversely, structural cracks due to foundation settlement and freezing and thawing deterioration to the walls or floor of a spillway will usually require repair, if not immediately, at some point in the future. Damage caused by absorptive aggregate popouts is common on bridge deck, canal, and dam concrete. Unless such concrete is exposed to high velocity waterflows, where the offsets caused by popouts can result in cavitation damage, repair can be ignored. Serious damage to a spillway should always be repaired. If the spillway, however, is constructed with a very thick slab and does not experience high velocity water flow, the repairs can be scheduled at some future date to allow an orderly process of budgeting

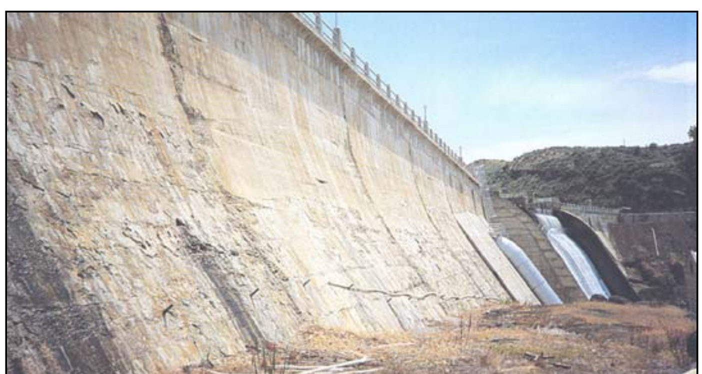
Figure 4-19 Freezing and thawing deterioration to the downstream face of this dam does not require repair for safe operation of the structure

to obtain the required funding. It should be noted, however, that proper maintenance might have eliminated the need to repair this spillway.

Selecting or scheduling the most optimum time to perform needed concrete repair should be part of the process of determining the need to repair. Except in emergencies, many irrigation structures cannot be removed from service during the water delivery season. The expense or loss of income involved with the inopportune release of reservoir water in order to lower water surface elevations to accomplish repairs may exceed the costs of the repairs by many times. If such costs exceed the value of the benefits expected from performing repairs, it might be prudent to postpone or even cancel performance of the repairs. Often damage on a spillway floor may initially be judged to be of a non-serious nature. Closer evaluation, however, may reveal that foundation material has been removed from a very large area beneath the floor slab and that immediate repair is required. If this spillway is operated without repair during periods of high spring runoff or flood flows, extensive additional damage might result. So, it is very important to make a proper evaluation of the need to make repairs, as well as when to make the repairs.

These first steps - determining the cause of damage, evaluating the extent of damage, and evaluating the need to repair - form the basis of what is known as a condition survey. If the damage is not extensive or if only a small part of a structure is involved, the condition survey could be simply a mental exercise. If major repair or rehabilitation is required, a detailed condition survey should be performed and documented. Such a survey will consist of review of the plans, specifications, and operating parameters for the structure; determination of concrete properties; and any additional field surveys, engineering studies, or structural analysis required to fully evaluate the present and desired conditions of the structure (American Concrete Institute, 1993). The final feature of a condition survey, completed only after the above-listed items have been completed, is a list of the recommended repair methods and materials.

4. Select the Repair Method

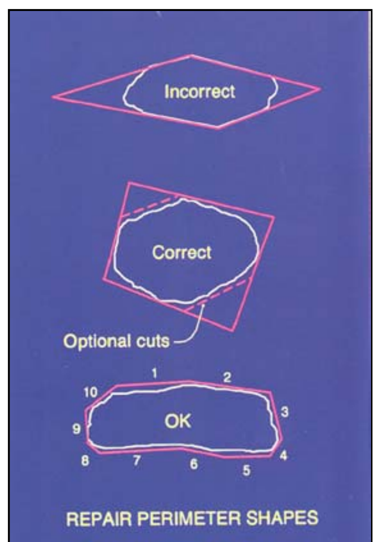

Figure 4-20 Saw cut patterns for the perimeters of repair areas.

There is a tendency to attempt selection of repair methods/materials too early in the repair process. This should be guarded against. With insufficient information, it is very difficult to make proper, economical, and successful selections. Once the above three steps of the repair process have been completed, or upon completion of a detailed condition survey, the selection of proper repair methods and materials usually becomes very easy. These steps define the types of conditions the repair must resist, the available repair construction time period, and when repairs must be accomplished. This information, in combination with data on the volume and area of concrete to be repaired, will usually determine which of the 15 standard repair materials should be used (described briefly below). Also, this information will determine when the standard repair materials cannot be expected to perform well and when nonstandard materials should be considered.

5. Prepare the Old Concrete for Repair

Preparation of the old concrete for application of the repair material is of primary importance in the accomplishment of durable repairs. The very best of repair materials will give unsatisfactory performance if applied to weakened or deteriorated old concrete. The repair material must able to bond to sound concrete. It is essential that all of the unsound or deteriorated concrete be removed before new repair materials are applied.

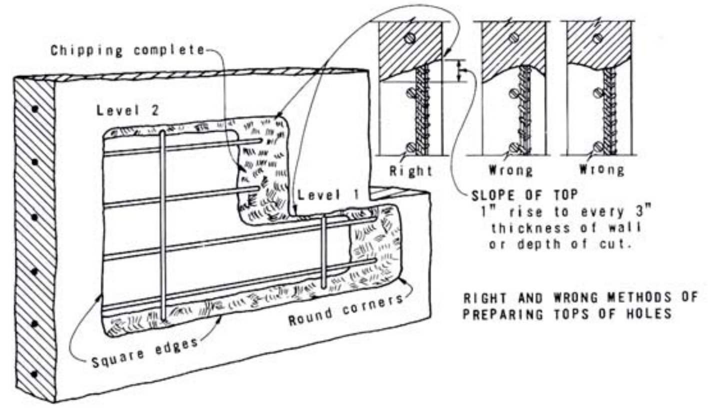

Figure 4-21 Preparation of a concrete deterioration that extends completely through a concrete wall.

The first step in preparing the old concrete for repair is to saw cut the perimeter of the repair area to a depth of 1 to 1.5 inches. The purpose of the saw cuts is to provide a retaining boundary against which the repair material can be compacted and consolidated. The perimeters of repairs are the locations most exposed to the effects of shrinkage, deterioration, and bond failure. Only poor compaction of repair material can be accomplished at feather edge perimeters. Such repair zones will fail quickly. For this reason feather edge perimeters to repair areas are not permitted by Reclamation's M-47 specifications. It is unnecessary to cut to the full depth of the repair, although to do so is not harmful. The saw cuts should be perpendicular to the concrete surface or tilted inward 2 to 3 degrees to provide retaining keyways that mechanically lock the repair material into the area. Tilting the saw inward more than 3 degrees may result in weak top corners in the old concrete and should be avoided. The saw cuts should never be beveled outward.

It is usually false economy to try to closely follow the shape of the repair area with a multitude of short saw cuts. The cost of sawing such a shape most likely will exceed the cost of increased repair area, and the resulting repair may be less attractive than those having simple rectangular shapes. Saw cuts should not meet in acute. It is very difficult to compact repair material into such sharp comers. The saw cut perimeters should have rounded comers whenever reasonable. Rounded corners cannot be cut with a circular concrete saw, but the cuts can be stopped short of the intersection and rounded using a jackhammer or bush hammer carefully held in a vertical orientation. It should be noted that intersections cannot be cut with a circular saw without the cuts extending outside the intersection. These cut extensions often serve as sources of cracking in some repair materials. Once the perimeters have been cut, the deteriorated concrete is removed using methods discussed in following paragraphs.

After the saw cut, all deteriorated or damaged concrete must be removed from the repair area to provide sound concrete for the repair material to bond to. It is always false economy to attempt to save time or money by shortchanging the removal of deteriorated concrete. Whenever possible, the first choice of concrete removal technique should be high pressure (8,000 to 15,000 pounds per square inch [psi]) hydroblasting or hydrodemolition. These techniques have the advantage of removing the unsound concrete while leaving high quality concrete in place. They have a further advantage in that they do not leave microfractured surfaces on the old concrete. Impact removal techniques, such as bushhammering, scrabbling, or jackhammering, can leave surfaces containing a multitude of microfractures which seriously reduce the bond of the repair material to the existing concrete. Subsequent removal of the microfractured surface by hydroblasting, shot blasting, or by wet or dry sandblasting should be performed if impact removal techniques are used. A disadvantage of the high pressure water blasting techniques is that the waste water and debris must be handled in an environmentally acceptable manner as prescribed by local regulations.

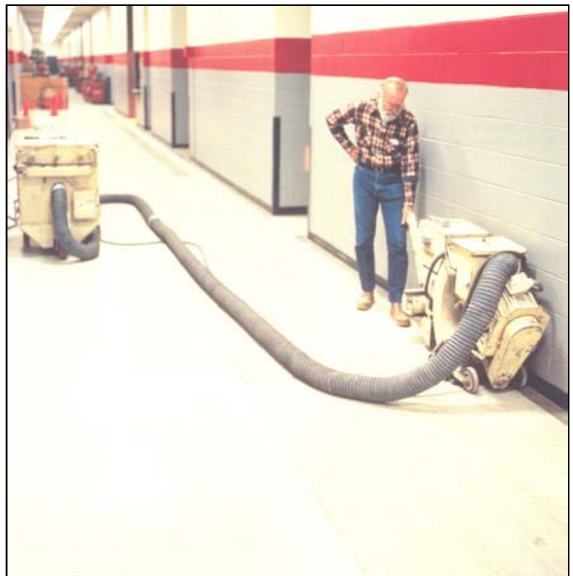

Figure 4-22 Shot blasting equipment used to remove shallow concrete deterioration.

Impact concrete removal techniques, such as jackhammering for large jobs and bushhammering for smaller areas, have been used for many years. These removal procedures are quick and economical, but it should be kept in mind that the costs of subsequent removal of the microfractured surfaces resulting from these techniques must be included when comparing the costs of these techniques to the costs of high pressure water blasting. The maximum size of jackhammers should usually be limited to 60 pounds. The larger jackhammers remove concrete at a high rate but are more likely to damage surrounding sound concrete. The larger hammers can impact and loosen the bond of concrete to reinforcing steel for quite some distance away from the point of impact. Pointed hammer bits, which are more likely to break the concrete cleanly rather than to pulverize it, should be used to reduce the occurrence of surface microfracturing.

Shallow surface deterioration (usually less than 1/2 inch deep) is best removed with shot blasting or dry or wet sandblasting. Shot blasting equipment is highly efficient and usually includes some type of vacuum pickup of the resulting dust and debris. The use of such equipment is much more environmentally acceptable than dry sand blasting. The need for removal of such shallow depths of deteriorated concrete is seldom encountered in concrete repairs other than for removal of microfractured surfaces or for cosmetic surface cleaning. Shallow deterioration to concrete surfaces can also be removed with tools known as scrabblers. These tools usually have multiple bits which pound and pulverize the concrete surfaces in the removal process. Their use greatly multiplies the microfractures in the remaining concrete surfaces. Extensive high pressure water, sand, or shot blasting efforts are then needed to remove the resulting damaged surfaces. Such efforts are seldom attained under field conditions. For this reason, Reclamation's M-47 specifications prohibit use of scrabblers for concrete removal.

Figure 4-23 Multiple bits on the head of a scrabbler pound and Pulverize the concrete surface during the removal process.

Reinforcing steel exposed during concrete removal requires special treatment. As a minimum, all scale, rust, corrosion, and bonded concrete must be removed by wire brushing or high pressure water or sand blasting. It is not necessary to clean the steel to white metal condition, just to remove all the loose or poorly bonded debris that would affect bond between the repair material and the reinforcing steel. If corrosion has reduced the cross section of the steel to less than 75 percent of its original diameter, the affected bars should be removed and replaced in accordance with section 12.14 of American Concrete Institute (ACI) 318 (ACI, 1992). Steel exposed more than one-third of its perimeter circumference should be sufficiently exposed to provide a 1-inch minimum clearance between the steel and the concrete.

After the repair area has been prepared, it must be maintained in a clean condition and protected from damage until the repair materials can be placed and cured. In hot climates, this might involve providing shade to keep the concrete cool, thereby reducing rapid hydration or hardening. If winter conditions exist, steps need to be taken to provide sufficient insulation and/or heat to prevent the repair area from being covered with snow, ice, or snowmelt water. It should be remembered that repair activities can also contaminate or damage a properly prepared site. Workmen placing repair materials in one area of a repair often track mud, debris, cement dust, or concrete into an adjacent repair area. Once deposited on a prepared surface, this material will serve as a bond breaker if not cleaned up before the new repair material is placed. Repair contractors should be required to repeat preparation if a repair area is allowed to become damaged or contaminated. The prepared concrete should be kept wet or dry, depending upon the repair material to be used. Surfaces that will receive polymer concrete or epoxy-bonded materials should be kept as dry as possible. Some epoxies will bond to wet concrete, but they always bond better to dry concrete. Surfaces that will be repaired with cementitious material should be in a saturated surface dry (SSD) condition immediately prior to material application. This condition is achieved by soaking the surfaces with water for 2 to 24 hours just before repair application. Immediately before material application, the repair surfaces should be blown free of water, using compressed air. The SSD condition prevents the old concrete from absorbing mix water from the repair material and promotes development of adequate bond strength in the repair material. The presence of free water on the repair surfaces during application of the repair material must be avoided whenever practicable.

6. Apply the Repair Method

There are 15 different standard concrete repair methods/materials in Reclamation's M-47 specification. Each of these materials has uniquely different requirements for successful application. These requirements and application procedures are briefly discussed below, and are discussed at length in Reclamation's "Guide to Concrete Repair."

7. Cure the Repair Properly

All of the standard repair materials, with the exception of some of the resinous systems, require proper curing procedures. Curing is usually the final step of the repair process, followed only by cleanup and demobilization, and it is somewhat common to find that the curing step has been shortened, performed haphazardly, or eliminated entirely as a result of rushing to leave the job or for the sake of perceived economies. It should be understood that proper curing does not represent unnecessary costs. Rather, it represents a sound investment in long-term insurance. Inadequate or improper curing can result in significant loss of money. At best, improper curing will reduce the service life of the repairs. More likely, inadequate or improper curing will result in the necessity to remove and replace the repairs. The costs of the original repair are, thus, completely lost, and the costs of the replacement repair will be greater because the replacement repairs will be larger and must include the costs of removal of the failed repair material.

Standard Methods of Concrete Repair

The Bureau of Reclamation's 15 proven methods of repairing concrete are briefly described below. Their "Guide to Concrete Repair" (Sections 24 through 38) contains detailed discussions of each of the proven repair methods. Construction specifications for these methods/materials of repair are contained in the latest revision of Reclamation's Standard Specifications for the Repair of Concrete, M-47, Appendix A. It is recommended that the provisions of these specifications be closely followed during repair of concrete. It should be recognized, however, that these "standard" methods and specifications cannot apply to unusual or nonstandard concrete repair situations. Assistance with unusual or special repair problems can readily be obtained by contacting personnel of Reclamation's Materials Engineering and Research Laboratories, Code 0-8180.

1. Surface Grinding

Surface grinding can be used to repair some bulges, offsets, and other irregularities that exceed the desired surface tolerances. Excessive surface grinding, however, may result in weakening of the concrete surface, exposure of easily removed aggregate particles, or unsightly appearance. For these reasons, surface grinding should be performed subject to the following limitations:

- Grinding of surfaces subject to cavitation erosion (hydraulic surfaces subject to flow velocities exceeding 40 feet per second) should be limited in depth so that no aggregate particles more than 1/16 inch in cross section are exposed at the finished surface.

- Grinding of surfaces exposed to public view should be limited in depth so that no aggregate particles more than 1/4 inch in cross section are exposed at the finished surface.
- In no event should surface grinding result in exposure of aggregate of more than one-half the diameter of the maximum size aggregate.

Where surface grinding has caused or will cause exposure of aggregate particles greater than the acceptable limits, the concrete must then be repaired by excavating and replacing the concrete.

2. Portland Cement Mortar

Figure 4-24 A Portland cement mortar patch seldom matches the color of the original concrete unless special efforts are taken to blend white cement with normal Portland cement.

Portland cement mortar may be used for repairing defects on surfaces not prominently exposed, where the defects are too wide for dry pack filling or where the defects are too shallow for concrete filling and no deeper than the far side of the reinforcement that is nearest the surface. Repairs may be made either by use of shotcrete or by hand application methods. Replacement mortar can be used to make shallow, small size repairs to new or green concrete, provided that the repairs are performed within 24 hours of removing the concrete forms.

Accomplishing successful mortar repairs to old concrete without the use of a bonding resin is unlikely or extremely difficult. Evaporative loss of water from the surface of the repair mortar, combined with capillary water loss to the old concrete, results in unhydrated or poorly hydrated cement in the mortar. Additionally, repair mortar bond strength development proceeds at a slower rate than compressive strength development. This causes workers to mistakenly abandon curing procedures prematurely, when the mortar "seems strong." Once the mortar dries, bond strength development stops, and bond failure of the mortar patch results. For these reasons, using cement mortar without a resin bond coat to repair old concrete is discouraged.

A portland cement mortar patch is usually darker than the surrounding concrete unless precautions are taken to match colors. A leaner mix will usually produce a lighter color patch. Also, white cement can be used to produce a patch that will blend with the surrounding concrete. The quantity of white cement to use must be determined by trial.

3. Dry Pack and Epoxy-Bonded Dry Pack

Dry pack is a combination of portland cement and sand passing a No. 16 sieve mixed with just enough water to hydrate the cement. Dry pack should be used for filling holes having a depth equal to, or greater than, the least surface dimension of the repair area; for cone bolt, she bolt, core holes, and grout-insert holes; for holes left by the removal of form ties; and for narrow slots cut for repair of cracks. Dry pack should not be used for relatively shallow depressions where lateral restraint cannot be obtained, for filling behind reinforcement, or for filling holes that extend completely through a concrete section.

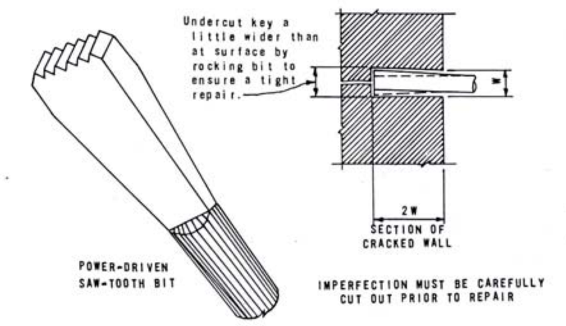

Figure 4-25 Saw-tooth bit used to cut slot for dry packing.

For the dry pack method of concrete repair, holes should be sharp and square at the surface edges, but corners within the holes should be rounded, especially when water tightness is required. The interior surfaces of holes left by cone bolts and she bolts should be roughened to develop an effective bond; this can be done with a rough stub of 7/8-inch steel-wire rope, a notched tapered reamer, or a star drill. Other holes should be undercut slightly in several places around the perimeter. Holes for dry pack should have a minimum depth of 1 inch.

4. Preplaced Aggregate Concrete

Preplaced aggregate concrete is an excellent repair material that has not been used much in recent years. Preplaced aggregate concrete is made by injecting portland cement grout, with or without sand, into the voids of a formed, compacted mass of clean, graded, coarse aggregate. The preplaced aggregated is washed and screened to remove fines before placing into the forms. As the grout is injected or pumped into the forms, it displaces any included air or water and fills the voids around the aggregate, thus creating a dense concrete having a high aggregate content.

Figure 4-26 The downstream face of Barker Dam, near Boulder, Colorado, was resurfaced with prepacked aggregate.

Because the coarse aggregate has point contact prior to grout injection, preplaced aggregate concrete undergoes very little settlement, curing, or drying shrinkage during hydration. Drying shrinkage of prep laced aggregate concrete containing 1-1/2 inch maximum size aggregate is about 200 to 400 millionths, while conventional concrete drying shrinkage containing the same size maximum aggregate is about 400 to 600 millionths.

Another advantage of preplaced aggregate concrete is the ease with which it can be placed in certain situations where placement of conventional concrete would be extremely difficult or impossible. Preplaced aggregate concrete is especially useful in underwater repair construction. It has been used in a variety of large concrete and masonry repairs, including bridge piers and the resurfacing of dams. It has been used to construct atomic reactor shielding and plugs for outlet works and tunnels in mine workings, and it has been used to embed penstocks and turbine scrollcases (American Concrete Institute, 1992).

Although preplaced aggregated is adaptable to many special repair applications, it is essential that the work be undertaken by well qualified personnel who are willing to follow exactly the construction procedures required for this repair material. Form work for preplaced aggregate concrete requires special attention to prevent grout loss. The construction of forms should be with workmanship better than that normally encountered with conventional concrete. Leaking forms can cause significant problems and should, by careful construction, be avoided whenever possible. The injected grout is more flowable than plastic concrete and takes slightly longer to set. Forms, therefore, must be constructed to take more lateral pressure than would be necessary with conventional concrete. Form bolts should fit tightly through the sheathing, and all possible points of grout leakage should be caulked.

5. Shotcrete

Figure 4-27 Wet mix shotcrete is propelled by compressed air.

Shotcrete is defined as "mortar or concrete pneumatically projected at high speed onto a surface" (American Concrete Institute, 1990). There are two basic types of shotcrete: dry mix and wet mix. In dry mix shotcrete, the dry cement, sand, and coarse aggregate, if used, are premixed with only sufficient water to reduce dusting. This mixture is then forced through the delivery line to the nozzle by compressed air. At the nozzle, sufficient water is added to the moving stream to meet the requirements of cement hydration. For wet mix shotcrete, the cement, sand, and coarse aggregate are first conventionally mixed with water, and the resulting concrete is then pumped to the nozzle where compressed air propels the wet mixture onto the desired surface. The two types of shotcrete produce mixes with different water contents and different application characteristics as a result of the distinctly different mixing processes. Dry mix shotcrete suffers high dust generation and rebound losses varying from about 15 percent to up to 50 percent. Wet mix shotcrete must contain enough water to permit pumping through the delivery line. Wet mix shotcrete, as a result, may experience significantly more cracking problems due to the excess water and drying shrinkage. Advances in the development of the high range water reducing admixtures, pumping aids, and concrete pumping equipment since about 1960 have greatly reduced these problems, and wet mix shotcrete is now being used more frequently in repair construction.

Figure 4-28 Dry mix shotcrete equipment showing the nozzle and water injection ring.

Shotcrete is a very versatile construction material that can be readily placed and successfully used for a variety of concrete repair applications. The necessity of form work can be eliminated in many repair applications by use of shotcrete. Shotcrete has been used to repair canal and spillway linings and walls, the faces of dams, tunnel linings, highway bridges and tunnels, deteriorating natural rock walls and earthen slopes, and to thicken and strengthen existing concrete structures. Provided the proper materials, equipment, and procedures are employed, such shotcrete repairs can be accomplished quickly and economically. This apparent ease of application should not cause one to believe that shotcrete repair is a simple procedure or one that can be haphazardly or improperly applied with impunity. The following two paragraphs contain a very descriptive warning of such practices:

"Regardless of the considerable advantages of the shotcrete process and its ability to provide finished work of the highest quality, a large amount of poor and sometimes unacceptable work has unfortunately occurred in the past, with the result that many design and construction professionals are hesitant to employ the process. As with all construction methods, failure to employ proper procedures will result in inferior work. In the case of shotcrete the deficiencies can be severe, requiring complete removal and replacement. Deficiencies in shotcrete applications usually fall into one of four categories: failure to bond to the receiving substrate, delamination at construction joints or faces of the application layers, incomplete filling of the material behind the reinforcing, and embedment of rebound or other unsatisfactory material" (Warner, 1995).

Each of the above-listed deficiencies has occurred on Reclamation repair projects. Perhaps more important with shotcrete than with any other standard concrete repair method, if highly qualified, well trained, and competent workmen cannot be employed, it is advisable to consider using some other repair procedure. The quality of shotcrete closely depends upon the skill and experience of one person, the nozzleman. Dam owners should use only formally certified nozzlemen for shotcrete repairs. The on-the-job training necessary to develop the experience and skill needed to achieve such certification for repair work should occur prior to the nozzleman's arrival at the job.

6. Replacement Concrete

Concrete repairs made by bonding new concrete to repair areas without use of an epoxy bonding agent or mortar grout applied on the prepared surface should be made when the area exceeds 1 square foot, has a depth greater than 6 inches, and when the repair will be of appreciable continuous area. Replacement concrete repairs should also be used for:

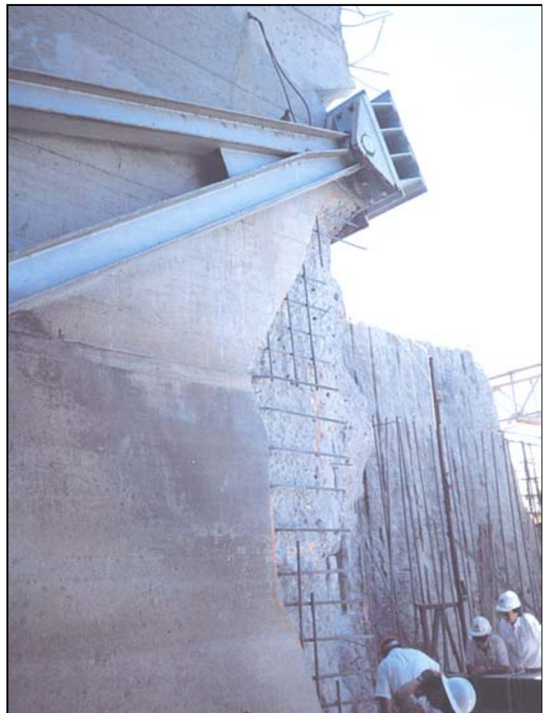
Figure 4-29 Preparation of a wall for placement of replacement concrete repairs.

- Holes extending entirely through concrete sections
- Holes in which no reinforcement is encountered, or in which the depth extends 1 inch below or behind the backside of the reinforcing steel and which are greater in area than 1 square foot and deeper than 4 inches, except where epoxy- bonded concrete replacement is required or permitted as an alternative to concrete replacement
- Holes in reinforced concrete greater than one-half square foot and extending beyond reinforcement

Replacement concrete is the most common concrete repair material and will meet the needs of a majority of all concrete repairs. Replacement concrete repairs are made by bonding new concrete to the repair areas without the use of a bonding agent or portland cement grout. The combination of a deep repair and good curing practices ensures adequate hydration water will remain at the bonding surface zone for at least 28 days, allowing the cement hydration process to develop good bond. Because the defective concrete is being replaced with high quality concrete very similar to the surrounding concrete, the repair is compatible in thermal expansion and in other physical and chemical properties with the old concrete. For this reason, in many cases, the best repair method is the use of replacement concrete. Only when an unusual increase in durability is needed, or when placing conditions or dimensions dictate otherwise, should other materials be considered.


Figure 4-30 A gas-fired forced air heater is being used to heat concrete prior to application of epoxy mortar.

7. Epoxy-Bonded Epoxy Mortar

Epoxy-bonded epoxy mortar should be used where the depth of repair is less than 1-1/2 inches and the exposure conditions are such that relatively constant temperatures can be expected. Epoxy mortars have thermal coefficients of expansion that may be significantly different from conventional concrete. If such mortars are used under conditions of wide and frequent temperature fluctuations, they will cause failure just below the bond surface in the base concrete. For this reason, epoxy mortars should not be used under conditions of frequent or large temperature variations.

The application of epoxy mortar to repair areas of concrete deterioration caused by corroding reinforcing steel is also not recommended. The epoxy bond coat and epoxy mortar create zones of electrical potential that are different from the electrical potential in the surrounding concrete. This difference in potential can result in the formation of a galvanic corrosion cell with accelerated corrosion at the repair perimeters.

Figure 4-31 Epoxy mortar is consolidated and compacted by hand tamping.

Epoxy mortar is properly used to make thin repairs (I/2-inch to 1-1/2-inch thickness) to concrete under relatively constant temperature exposure conditions. Such applications could include tunnel linings, indoor or interior concrete, the underside of concrete structures such as bridge decks, continuously inundated concrete such as stilling basin floors, canal linings below water line, or concrete pipe. Applications to concrete exposed to the daily temperature fluctuations caused by exposure to direct sunlight are not appropriate for epoxy mortar repair.

Figure 4-32 Applying the steel trowel finish required by epoxy mortar repairs.

Properly applied epoxy mortar repairs have a long history of successful performance on repaired concrete when used under appropriate conditions. A 1991 inspection of the epoxy mortar repairs made at Yellowtail Dam in 1968 showed that less than 2 percent of the repairs had suffered failure in over 20 years of service. This is considered out-standing performance for a repair material.

Figure 4-33 The placement techniques for epoxy-bonded concrete are essentially the same as for conventional concrete.

8. Epoxy-Bonded Replacement Concrete

Epoxy-bonded concrete is used for repairs to concrete that are between 1.5 and 6 inches thick. Shallow replacement concrete repairs, less than 6 inches thick, are subject to poor curing conditions as a result of moisture loss to evaporation and to capillary absorption by the old base concrete. Such repairs seldom develop acceptable bond strength to the old concrete. The epoxy bonding resin is used to ensure a strong, durable bond between the old concrete and the replacement concrete.

As with epoxy-bonded epoxy mortar, care should be exercised if epoxy-bonded concrete is to be used to repair shallow deterioration resulting from corroding reinforcement. The epoxy bond coat may create electrical potentials sufficiently different from potentials in the surrounding concrete to result in accelerated corrosion at repair perimeters.

9. Polymer Concrete

Polymer concrete (PC) is a concrete system composed of a polymeric resin binder and fine and coarse aggregate. Water is not used to mix polymer concrete. Instead, the liquid resin, known as a monomer, is caused to cure or harden by a chemical reaction known as polymerization. During polymerization, the monomer molecules are chemically linked and cross linked to form a hard, glassy plastic known as a polymer. The polymers used in PC are formulated to provide the special properties needed for high performance repair materials.

These systems can be cured very quickly and are most useful in performing repairs to structures that must be immediately returned to service. As an example, PC is commonly used to repair potholes in concrete highway bridge decks, thereby eliminating the necessity of long and costly road closures or detours. It is also useful for repairs to structures, such as tunnel linings, that can be maintained in a dry condition for only short periods of time and for cold weather repairs down to temperatures as low as 15 degrees Fahrenheit. PC repairs can be accomplished in thicknesses varying from about 1/2 inch to several feet if appropriate precautions are taken.

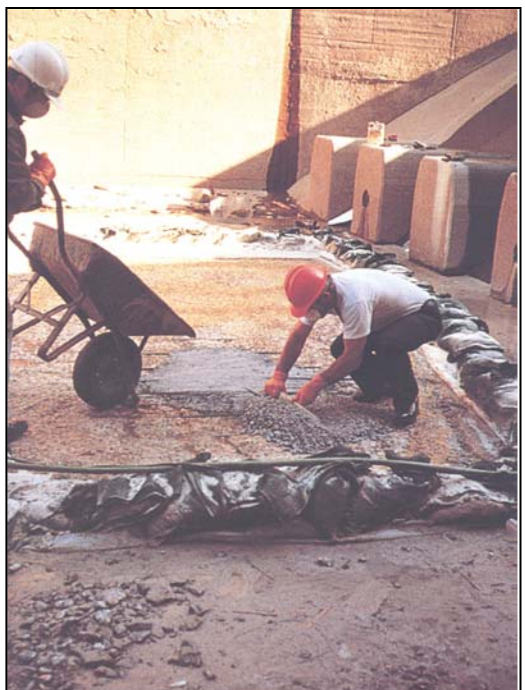

Figure 4-34 Placing polymer concrete in a repair area. Sandbags and polyethylene sheeting were used to prevent water from entering the repair area.

PC develops strength and durability properties very quickly due to its rapid polymerization characteristics and is useful where rapid repairs to concrete are required. PC can be mixed, placed, polymerized, and put into service in only a matter of hours. PC also develops enhanced durability properties. This feature makes it useful as protective overlays on conventional concrete exposed to corrosive or severe environments. Since PC does not contain mix water, it can be used at much lower temperatures (down to 15 degrees Fahrenheit) than portland cement concrete.

Most polymer concretes experience some volumetric shrinkage during polymerization and also have problems associated with the coefficient of thermal expansion similar to those experienced with epoxy mortars. These problems with PC, though generally less severe than similar problems with epoxy mortar, can limit the materials use on concrete exposed to wide temperature variations. Potential users of PC should be aware of these problems. Reclamation's Materials Engineering and Research Laboratory at Denver, 0-8180, can provide guidance and recommendations for the application of these very useful materials.

10. Thin Polymer Concrete Overlay

Figure 4-35 Small stinger vibrators can be used to consolidate shallow depths of polymer concrete.

The thin PC overlay is a hard, glassy concrete coating, 25 to 50 mils thick, consisting of a vinyl ester resin system, silica flour filler, and appropriate coloring pigments. This membrane-forming overlay partially penetrates the immediate top surface of the concrete and provides very good protection to concrete exposed to adverse chemical or weathering conditions. It can also provide cosmetic treatment to concrete exposed to public view. The normal three-coat application of this material (one primer coat plus two filler coats) should result in a total overlay thickness of about 50 mils.

Figure 4-36 Polymer concrete must be protected from water and not disturbed during the 1- to 2-hour curing period. No other curing procedures are required unless ambient temperatures are very low.

The overlay is applied to protect the concrete from water penetration and resulting freeze-thaw damage; to protect the concrete from chemical corrosive elements such as acids, chlorides, or sulfates; and/ or to improve the cosmetic appearance of the concrete. The overlay provides complete opaque coverage of the concrete surface and flows into and seals narrow cracks in the surface. There is currently no known commercial manufacturer of the thin polymer concrete overlay. Contractors or users of the overlay system can have the material prepared by custom resin blenders or can blend and mix the material themselves using the formulas listed in the "Guide to Concrete Repair."

11. Resin Injection

Resin injection is used to repair concrete that is cracked or delaminated and to seal cracks in concrete to water leakage. Two basic types of resin and injection techniques are used to repair concrete.

1. Epoxy Resins

Figure 4-37 Commercial polyurethane injection pump.

Epoxy resins cure to form solids with high strength and relatively high moduli of elasticity. These materials bond readily to concrete and are capable, when properly applied, of restoring the original structural strength to cracked concrete. The high modulus of elasticity causes epoxy resin systems to be unsuitable for rebonding cracked concrete that will undergo subsequent movement. Epoxy resin has been used to seal cracks in concrete to water flow. The epoxies, however, do not cure very quickly, particularly at low temperatures, and using them to stop large flows of water may not be practical. Cracks to be injected with epoxy resins should be between 0.005 inch and 0.25 inch in width. It is difficult or impossible to inject resin into cracks less than 0.005 inch in width, while it is very difficult to retain injected epoxy resin in cracks greater than 0.25 inch in width, although high viscosity epoxies have been used with some success. Epoxy resins cure to form relatively brittle materials with bond strengths exceeding the shear or tensile strength of the concrete. If these materials are used to rebond cracked concrete that is subsequently exposed to loads exceeding the tensile or shear strength of the concrete, it should be expected that the cracks will recur adjacent to the epoxy bond line. In other words, epoxy resin should not be used to rebond "working" cracks.

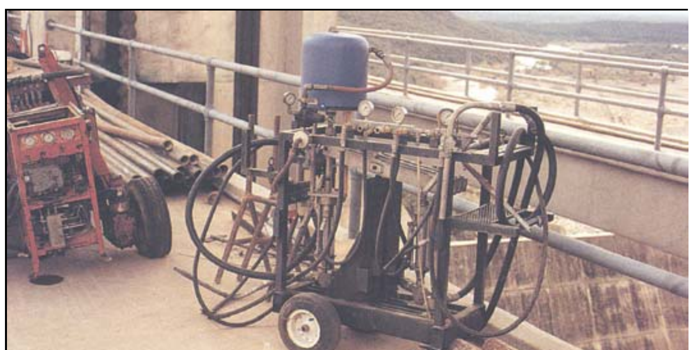

Figure 4-38 This is an air-powered pump system used for large scale polyurethane resin injection.

Epoxy resins will bond with varying degrees of success to wet concrete, and there are a number of special techniques that have been developed and used to rebond and seal water leaking cracks with epoxy resins. These special techniques and procedures are highly technical and, in most cases, are proprietary in nature. They may have application on repair projects, but only after a thorough analysis has been performed to ensure that the more standard repair procedures will not be successful or cost effective.

2. Polyurethane Resins

Polyurethane resins are used to seal and eliminate or reduce water leakage from concrete cracks and joints. They can also be injected into cracks that experience some small degree of movement. Such systems, with the exception of the two-part solid polyurethanes, have relatively low strengths and should not be used to structurally rebond cracked concrete. Cracks to be injected with polyurethane resin should not be less than 0.005 inch in width. No upper limit on crack width has been established for the polyurethane resins at the time this is being written.

Polyurethane resins are available with substantial variation in their physical properties. Some of the polyurethanes cure into flexible foams. Other polyurethane systems cure to semi-flexible, high density solids that can be used to rebond concrete cracks subject to movement. Most of the foaming polyurethane resins require some form of water to initiate the curing reaction and are, thus, a natural selection for use in repairing concrete exposed to water or in wet environments. At the time this is written, there are no standard specifications for polyurethane resins equivalent to the Standard Specification for Epoxy-Resin-Base Bonding Systems for Concrete, ASTM Designation C-881. This current lack of standards, combined with. the wide variations possible in polyurethane physical properties, creates the necessity that great care be exercised in selecting these resins for concrete repair. "Cookbook" type application of these resins will not be successful. The Materials Engineering and Research Laboratory (0-8180) of the Denver Technical Services Center is currently testing and evaluating these very useful resin systems. They will provide advice and guidance for field applications if requested.

Because of the relatively high cost to repair cracks using resin injection, this method is not normally used to repair shallow, drying shrinkage, or pattern cracking.

12. High Molecular Weight Methacrylic Sealing Compound

Concrete sealing compounds are applied to cured, dry concrete as a maintenance procedure to reduce or prevent penetration of water, aggressive solutions, or gaseous media and the associated deterioration, such as freeze-thaw, carbonation, or sulfate damage. These materials replace the linseed oil based treatment, which was generally misunderstood and is no longer recommended for use on concrete.

A variety of different membrane forming (similar to paints or coatings) and surface penetrating chemicals are manufactured and sold as sealing compounds for concrete surfaces. Some of these materials provide very good protection to the concrete for discrete periods of time. Other commercially available sealing materials, however, may be little more than mineral spirits and linseed oil. Such systems will, at best, do little harm to the concrete. Their application may, however, prevent subsequent treatment with the sealing compounds that have been proven effective. For this reason, only productucts that have proven effective in Reclamation laboratory tests and field applications should be used on repair projects. Reclamations Materials Engineering and Research Laboratory, D-8180, maintains a current listing of concrete sealing compounds that have been found effective for Reclamation applications.

One type of sealing; compound that has proven effective in Reclamation laboratory tests and field applications and has been designated a Standard Repair Material is known as a high molecular weight methacrylic monomer system. This sealing compound is composed of a methacrylic monomer and appropriate polymerization "catalysts" very similar to the monomer system used in polymer concrete. It is a water thin, amber colored liquid that is easily spread over horizontal and vertical concrete surfaces with brooms or squeegees.

The liquid penetrates the concrete surface to a depth of about 1/16 inch but is most effective in penetrating and sealing cracks in the concrete surface. This sealer will act like a membrane forming system if excess monomer is applied or if two or more applications are made. The appearance of the concrete following application will be somewhat like a varnished or water wet surface and may be splotchy in areas of high and low absorption. Cured sealer left on the surface of the concrete will be deteriorated by solar radiation within 1 to 2 years and will disappear. The loss of this surface material is of no consequence since the objective of the application is to penetrate and seal cracks where the sealer is protected from solar radiation deterioration. The expected service life of properly applied methacrylic sealing compound under typical Western State climatic conditions is 10 to 15 years. Reapplication is then necessary.

13. Polymer Surface Impregnation

The polymer surface impregnation process was developed by the Bureau of Reclamation for the Federal Highway Administration to prevent chloride deicing salt penetration and subsequent corrosion of reinforcing steel in existing concrete highway bridge decks. The process has provided in excess of 20 years of highly successful protection to many highway bridge decks and was applied to the entire roadway surface over Reclamation's Grand Coulee Dam.

In this process, the concrete to be treated is first covered with a bed of sand and dried with heat to remove moisture from the zone to be impregnated. A low viscosity methyl methacrylic monomer system is applied to the sandbed under a heavy polyethylene sheet and allowed to soak into the concrete surface for about 6 hours. The polyethylene retards evaporation of the highly volatile monomer system, and the sand acts as a reservoir, retaining the monomer system on the concrete until it soaks into the surface. The polyethylene covered sand and treated surface is then reheated to initiate insitu polymerization of the methyl methacrylate monomer system within the structure of the concrete. Concrete so treated will be virtually impervious to water absorption and freeze-thaw deterioration.

Figure 4-39 This workman is hand screeding a small silica fume concrete repair.

Detailed materials and performance specifications for the polymer surface impregnation process are contained in “Guide to Concrete Repair.” Users considering application of this procedure should carefully appraise the current costs and associated safety issues. The costs of energy to properly dry and reheat areas of concrete may preclude large scale use of this very effective preventative maintenance process.

14. Silica Fume Concrete

Silica fume concrete is conventional portland cement concrete containing admixtures of silica fume. Silica fume is a finely divided powder byproduct resulting from the use of electric arc furnaces. When mixed with portland cement concrete, silica fume acts as a "super pozzolan." Concrete containing 5 to 15 percent silica fume by mass of cement commonly can develop 10,000-psi to l5,000-psi compressive strengths, reduced tendency to segregate, very low permeabilities, and enhanced freeze-thaw and abrasion-erosion resistance. Current use of silica fume is primarily for the purpose of enhancing or improving concrete durability with less emphasis on strength improvement.

Silica fume concrete is the repair material of choice for applications requiring enhanced abrasion-erosion resistance and/ or reduced permeability. Silica fume concrete requires a very thorough curing procedure, however, and should not be used unless such a procedure can be accomplished. Otherwise, this repair material is used in accordance with the provisions for conventional replacement concrete.

The silica fume admixture can be obtained in at least three forms for use in concrete:

(1) Silica fume powder
(2) Densified silica fume powder with or without a high range water reducing admixture (HRWRA) and other dry admixtures
(3) Silica fume-water slurry with HRWRA and other admixtures

The dry silica fume powder is difficult to use because of its extremely small particle size. The fine powder drifts and spreads in any draft or air movement and can create silicate respiratory problems to workers. The water slurry form is easy to use, creates no dust problems, but does involve an additional mixing step as the slurry settles during storage and shipment and must be stirred and remixed prior to use. The water in the slurry must be accounted during mix design. Transportation costs of the slurry must also be considered. The densified powder form is currently the most convenient form to ship and use. In this form, the silica fume powder is compacted and densified and does not produce nearly the quantity of dust that occurs with the powdered form. It is a dry material and does not create additional shipping costs. Because it has been compacted into clumps, it should be expected that additional time would be required during mixing to fully break up and disperse the densified silica fume admixture in the concrete mixture.

Because of these various forms, it is essential that trial mixtures be prepared and tested during mix design to ensure development of the desired concrete properties.

The addition of silica fume admixture to concrete will increase the water requirement due to the high surface area of the very fine silica fume particles. The use of HRWRA is thus necessary to obtain the maximum strength and durability with silica fume concrete. Provisions should be made during proportioning, however, to accommodate the slump gain commonly associated with concrete containing HRWRA. Silica fume increases the cohesion or "stickiness" of the concrete and can result in workability and finishing problems for those inexperienced in the proper finishing techniques. It is of primary importance to place and finish silica fume quickly, before excessive mix water evaporation and stiffening occurs. The slump gain from the HRWRA commonly offsets some of the "stickiness" of silica fume concretes. Typical requirements include 4-6 percent entrained air in silica fume concrete. This addition of air entraining admixture also improves the workability of the concrete.

Special repair techniques are required for restoration of damaged or eroded surfaces of spillway or outlet works tunnel inverts and stilling basins. In addition to the usual forces of deterioration, such repairs often must withstand enormous dynamic and abrasive forces from fast-flowing water and sometimes from suspended solids. The enhanced abrasion-erosion resistance and high strength of silica fume concrete makes it the repair material of choice for these types of repair. It should be recognized, however, that the cause(s) of the original damage in such repairs must be mitigated if a permanent repair is to be accomplished.

Whenever practicable, low slump silica fume concrete should be used for these types of repair. Slump of the concrete should not exceed 2 inches for slabs that are horizontal or nearly horizontal and 3 inches for all other concrete. (This is 1 inch less slump than required in the M-47 specifications for conventional applications of silica fume concrete.) The net water-cementitious ratio (exclusive of water absorbed by the aggregates) should not exceed 0.35, by weight. An air-entraining agent should be used, and a high range water reducing admixture should be used. Set-retarding admixtures should be used only when the interval between mixing and placing is quite long.

15. Alkyl-Alkoxy Siloxane Sealing Compound

This sealing compound is effective in reducing water penetration into treated concrete, provided that the sealing compound contains in excess of 15-percent siloxane solids. These solids are suspended in a carrier such as alcohol or mineral spirits that evaporates from the concrete following application. Use of this type of sealing compound does not cause a change in the appearance of the treated concrete, except that the darkening normally associated with water wetting of concrete does not occur. It is common to see water bead on treated concrete surfaces. Siloxane sealing compounds will not provide protection to concrete that is completely inundated in water

Figure 4-40 A paint roller application of siloxane sealing compound to the downstream face on Nambe Falls Dam, near Sante Fe, New Mexico.

except for short periods. They should not be used under conditions that involve prolonged inundation such as occurs with stilling basins, canal floors, or spillway floors unless there are significantly long dry periods between inundations and it is acceptable to reapply the sealing compound following inundation. Siloxane sealing compound is best used to protect concrete from rain, snowmelt, and water splash zones.

These materials have a relatively limited service life, and reapplication should be scheduled about every 5 to 7 years for optimum protection. Application of these materials, however, proceeds very quickly on horizontal and vertical concrete surfaces. Two workmen can be expected to treat 10,000 to 15,000 square feet of horizontal surface in a day.

Nonstandard Methods of Repair

The standard concrete repair methods/materials discussed earlier will meet nearly all concrete repair needs. There will be occasions, however, resulting from unusual causes of damage and exposure conditions or special repair needs, when the standard repair methods may not meet the performance needs. In these infrequent instances, nonstandard repair methods may be required.

Repair materials are considered to be nonstandard if they have not been thoroughly tested and evaluated for Reclamation applications. The use of such materials involves a certain element of risk because the performance properties of these materials are unknown or not fully defined. The application of nonstandard materials can be justified only when it has been determined that no standard repair material will serve, and if all parties associated with or responsible for accomplishing the repairs are made to understand the risks and agree to accept the uncertainties and possible consequences.

An example of such a situation would be the need to repair concrete damage on the crest of a dam that is less than 1-1/2 inches deep. There is no standard repair material suitable for such shallow repairs when exposed to sunlight temperature variation conditions. (These conditions eliminate the use of epoxy mortars.) The current standard repair material for depths between 1-1/2 inches and 6 inches is epoxy-bonded replacement concrete. If the deterioration is not at least 1-1/2 inches deep, sufficient concrete must be removed to accomplish a 1-1/2- inch depth. If, for some reason, it was undesirable or impossible to remove the required depth of concrete, it might be appropriate to select one of the proprietary thin repair products. These materials have been only partially evaluated (Smoak and Husbands, 1996) and the long-term field performance has not yet been fully determined. In this example, the dam owner must be made aware of the risks of using an unproven repair material must be made known to them. The dam owner, with this knowledge, can then determine if the benefits of performing the shallower repairs would outweigh the uncertainties associated with unproven performance.

4.10 ACCESS ROADS

For a dam to be operated and maintained, there must be a safe means of access to it at all times. The road surface must be maintained to allow safe passage of automobiles and any required equipment for servicing the dam, in any weather conditions. Routine observations of any cut and fill slopes along the sides of the road should be made. If unstable conditions develop, professional help should be obtained and remedial measures initiated.

Figure 4-41 This dam has an access road that crosses the embankment; however lack of a durable road surface creates potential erosion problems and safety concerns.

Generally, a drainage ditch is required along roads in cuts to remove surface and subsurface drainage. This will prolong the life of the road and help reduce deterioration from rutting and freeze-thaw action.

Road surfacing should be repaired or replaced as necessary to maintain the required traffic loadings. In most cases, specialized contractors will be required to perform this maintenance.

4.11 MECHANICAL EQUIPMENT

Proper operation of a dam's outlet works is essential to the safe and satisfactory operation of a dam. Release of water from a dam is normally a frequent or ongoing function. However, on some reservoirs used for recreation, fish propagation, or other purposes that do not require continual release of water, an operable outlet provides the only means for the emergency lowering of the reservoir and is therefore, essential for the safety of the dam.

If routine inspection of the outlet works indicates the need for maintenance, the work should be completed as soon as access can be gained. Postponement of maintenance could cause damage to the installation, significantly reduce the useful life of the structure, and result in more extensive and more costly repairs when finally done. More importantly, failure to maintain an outlet system can lead directly to failure of the dam.

The simplest procedure to insure the smooth operation of outlet gates is to operate all gates through their full range at least once and preferably twice annually. Many gate manufacturers recommend operating gates as often as four times a year. Because operating gates under full reservoir pressure can result in large outlet discharges, gate testing should be scheduled during periods of low storage. If this cannot be done, they should be operated during periods of low stream flow. If large releases are expected, outlets should be tested only after coordinating releases with water administration officials and notifying downstream residents and water users.

Operation of the gates minimizes the buildup of rust in the operating mechanism and therefore, the likelihood of seizure of the operating mechanism. During this procedure, the mechanical parts of the hoisting mechanism - including drive gears, bearings, and wear plates - should be checked for adverse or excessive wear, all bolts, including anchor bolts, should be checked for tightness, worn and corroded parts should be replaced, and mechanical and alignment adjustments should be made as necessary.

The way the gate actually operates should also be noted. Rough, noisy, or erratic movement could be the first signs of a developing problem. The cause of operational problems should be investigated and corrected immediately. Excessive force should be neither needed nor applied to either raise or lower a gate. Most manual hoisting mechanisms are designed to operate satisfactorily with a maximum force of 40 pounds on the operating handle or wheel. If 40 pounds force is exceeded, the operating stem may be bent and the gate become inoperable. Electric-motor operated floor stands should have torque limiting devices; limit switch settings should be checked to prevent operating stem damage. If excessive force seems to be needed, something may be binding the mechanical system. The application of excessive force may result in increased binding of the gate or damage to the outlet works. If there does seem to be undue resistance, the gate should be worked up and down repeatedly in short strokes until the binding ceases, and/or the cause of the problem should be investigated. Of course, the problem should be corrected as soon as possible to assure the continued operability of the gate.

If a gate does not properly seal when closed, debris may be lodged under or around the gate leaf or frame, or the stem is bent. The gate should be raised at least 2 to 3 inches to flush the debris, and the operator should then attempt to re-close the gate. This procedure should be repeated until proper sealing is achieved. However, if this problem or any other problem persists, a manufacturer's representative or engineer experienced in gate design and operation should be consulted.

An outlet gate operating mechanism should always be well lubricated in accordance with manufacturer's specifications. Proper lubrication will not only reduce wear in the mechanism, but also protect it against adverse weather. Gates with oil-filled stems (i.e., stems encased in a larger surrounding pipe) should be checked semiannually to assure the proper oil level is maintained. If such mechanisms are neglected, water could enter the encasement pipe through the lower oil seal and could cause failure of the upper and/or lower seals which in turn could lead to the corrosion of both the gate stem and interior of the encasement pipe.

Depending on the type of gate operated, there may be vibration in the system and eventually fasteners will become loose and affect stem guide alignment. For satisfactory operation, a gate stem must be maintained in proper alignment with the gate and hoisting mechanism. Proper alignment and support is supplied by stem guides in sufficient number and properly spaced along the stem. Stem guides are brackets or bearings through which a stem passes. They both prevent lateral movement of the stem and bending or buckling when a stem is subjected to compression as a gate is being closed. The alignment of a stem should be checked during routine inspections. Alignment may be checked by sighting along the length of the stem, or more accurately by dropping a plumb line from a point near the top of the stem to the other end. The stem should be checked in both an upstream/downstream direction as well as in a lateral direction to ensure straightness. While checking alignment, all gate stem guide anchors and adjusting bolts should be checked for tightness. A loose guide provides no support to the stem and could cause buckling of the stem at that point. If during normal inspection, the stem appears out of alignment, the cause should be repaired. The gate should be completely lowered and all tension or compression taken off the stem. Any misaligned stem guides should be loosened and made to move freely. The hoisting mechanism should then be operated to put tension on the stem, thereby straightening it, but the gate should not be opened. The affected guides should then be aligned and fastened so that the stem passes exactly through their centers.

The metal used in gate seats is usually brass, stainless steel, bronze, or other rust-resistant alloys. Older or smaller gates may not be fitted with seats, making them susceptible to rusting at the contact surfaces between the gate leaf and gate frame. Operation of gates should prevent excessive rust buildup or seizure. Many outlet gates are equipped with wedges that hold the gate leaf tightly against the gate frame as the gate is closed, thus causing a tight seal. Through years of use, gate seats may become worn, causing the gate to leak increasingly. If an installation has a wedge system, the leakage may be substantially reduced or eliminated by readjusting or replacing the wedges. Because adjustment of these gates is complicated, inexperienced personnel can cause extensive damage to a gate. Improper adjustment could cause premature seating of the gate, possible scoring of the gate seats, binding of the gate, gate vibration, leakage, uneven closing of the gate, or damage to wedges or gate guides. Thus, only experienced personnel should perform adjustments, and a gate supplier or manufacturer should be consulted to obtain names of people experienced in such work.

Ice can exert great force on and cause significant damage to an outlet gate leaf. Storage levels in a reservoir during winter should be low enough that ice cannot form behind a gate. To prevent ice damage, the winter water level should be significantly higher than the gate if storage is maintained through the winter or, if the reservoir is to remain empty over the winter months, the outlet should be left fully open. If operations call for the water level to move across the gate during the winter, a bubbler or other anti-icing system may be needed.

All exposed, bare ferrous metal on an outlet installation, whether submerged or exposed to air, will rust. To prevent corrosion, exposed ferrous metals must either be painted or heavily greased. If painted, the paint should be appropriate and applied following the paint manufacturer's directions. When areas are repainted, steps should be taken to assure that paint does not get on gate seats, gate wedges, or gate stems where the stems pass through the stem guides, or on other friction surfaces where paint could cause binding. Heavy grease should be used on surfaces where binding can occur. Because rust is especially damaging to contact surfaces, existing rust should be removed before the periodic application of grease.


Figure 4-42 Tainter gates are used in this concrete spillway system.

Electrical equipment is typically used at a dam to provide lighting, operate outlet gates, operate recording equipment, operate spillway gates, and operate other miscellaneous equipment. It is important that an electrical system be well maintained. Maintenance should include a thorough check of fuses, circuit breakers, and a test of the system to ensure that all parts are properly functioning. The electrical system should be free from moisture and dirt, and wiring should be checked for corrosion and mineral deposits. Any necessary repairs should be completed immediately, and records of the repair work should be kept. Stationary and portable generators used for auxiliary emergency power must also be maintained. This work includes changing oil, and checking batteries and antifreeze.

Monitoring devices for the most part do not require routine maintenance. The main exceptions are the piezometers, weirs, and stakes (in staked areas). The weirs should be regularly checked and cleared of any debris. They should also be checked for loose boards or loose metal stripping, and repaired as necessary. Staked areas are particularly susceptible to vandalism. Stakes should be checked routinely and replaced immediately where needed. Piezometers should be maintained in an operable state at all times. Consult the recommendations of the manufacturer for guidelines on maintenance.

4.12 MONITORING REPAIRS

After repairs are completed on the dam or its appurtenant works, they should be monitored on a regular basis to insure that the repairs were effective. Monitoring should be performed frequently initially; the frequency can be reduced in time after the dam owner is “comfortable” with the results. Photographs and notes should be taken to help keep an accurate record.

4.13 RODENT CONTROL

Rodents such as the groundhog (woodchuck), muskrat, and beaver are attracted to dams and reservoirs and can be quite dangerous to the structural integrity and proper performance of the embankment and spillway. Groundhogs typically burrow into the downstream slope while muskrats and sometimes beavers burrow into the upstream slope from below the water line. Collapse of the burrow can result in a hole in the crest of the dam. Burrows weaken the embankment and can serve as pathways for seepage. Beavers may plug the spillway and raise the reservoir level. Rodent control is essential in preserving a well-maintained dam.

The groundhog is the largest member of the squirrel family. Their average life expectancy is 2 or 3 years with a maximum of 6 years. Occupied groundhog burrows are easily recognized in the spring due to the groundhog's habit of keeping them "cleaned out." Fresh dirt is generally found at the mouth of active burrows. Half-round mounds and paths leading from the den to nearby fields also help identify inhabited burrows and dens.

When burrowing into an embankment, groundhogs stay above the phreatic surface (saturated zone) to stay dry. The burrow is rarely a single tunnel. It is usually forked, with more than one entrance and with several side passages or rooms from 1 to 12 feet long.


Figure 4-43 This groundhog hole should be checked for activity and backfilled after any rodents (if found) are removed.

Control methods should be implemented during early spring when active burrows are easy to find, young groundhogs have not scattered, and there is less likelihood of damage to other wildlife. In later summer, fall, and winter, game animals will scurry into groundhog burrows for brief protection and may even take up permanent abode during the period of groundhog hibernation. Groundhogs can be controlled by using fumigants or removal. Fumigation is the most practical method of controlling groundhogs. Around buildings or other high fire hazard areas, shooting may be preferable. Groundhogs will be discouraged from inhabiting the embankment if the vegetal cover is kept mowed. Information about the control of groundhogs may be obtained from IDNR.

The muskrat is a stocky rodent with a broad head, short legs, small eyes, and rich dark brown fur. Muskrats are chiefly nocturnal. Their life expectancy is less than 2 years, with a maximum of 4 years. Muskrats can be found wherever there are marshes, swamps, ponds, lakes, and streams having calm or very slowly moving water, with vegetation in the water and along the banks. Muskrats make their homes by burrowing into the banks of lakes and streams. Their burrows begin from 6 to 18 inches below the water surface and penetrate the embankment on an upward slant. At distances up to 15 feet from the entrance, a dry chamber is hollowed out above the water level. Once a muskrat den is occupied, a rise in the water level will cause the muskrat to dig farther and higher to excavate a new dry chamber. Damage (and the potential for problems) is compounded where groundhogs or other burrowing animals construct their dens in the embankment opposite muskrat dens.

Barriers to prevent burrowing offer the most practical protection to earthen structures. A properly constructed riprap and filter layer will discourage burrowing. The filter and riprap should extend at least 3 feet below the water line. As the muskrat attempts to construct a burrow, the sand and gravel of the filter layer caves in and thus discourages den building. Heavy wire fencing laid flat against the slope and extending above and below the waterline can also be effective. Eliminating or reducing aquatic vegetation along the shoreline will discourage muskrat habitation.

Trapping with steel traps is usually the most practical method of removing muskrats from a reservoir. Owners should contact IDNR for regulations concerning trapping.

The recommended method of backfilling a groundhog or muskrat burrow on an embankment is mudpacking. This simple, inexpensive method can be accomplished by placing one or two lengths of metal stove or vent pipe in a vertical position over the entrance of the den. After it is certain that the pipe connection to the den does not leak, the mud-pack mixture is poured into the pipe until the burrow and pipe are filled with the earth-water mixture. The pipe is removed and dry earth is tamped into the entrance. The mud-pack is made by adding water to a 90 percent earth and 10 percent cement mixture until a slurry or thin cement consistency is attained. All entrances should be plugged with well-compacted earth and vegetation established. Dens should be eliminated without delay because damage from just one hole can lead to failure of a dam or levee.

Beaver will try to plug spillways with their cuttings. Routinely removing the cuttings is one way to alleviate the problem. Another successful remedy is the placement of electrically charged wire or wires around the spillway inlet. Trapping beaver may be done by the owner during the appropriate season; however, IDNR should be contacted to determine the proper seasons and techniques.

4.14 MAINTENANCE RECORDS

Thorough maintenance records are of utmost importance. A record should be kept of all maintenance activities, both preventive and repair maintenance work. Information that should be recorded includes the following as a minimum:

- date and time of maintenance
- weather conditions
- the type of maintenance
- name of person or contractor performing maintenance
- description of work performed
- the length of time it took to complete the work

- equipment and materials used
- before and after photographs

The data should be recorded by the person responsible for maintenance.

APPENDICES

APPENDIX A

SAMPLE BACKGROUND DATA SHEET

Dam Background Data Sheet

1. General Information

Owner's Name		Owner's Address	
Owner's Telephone			
County		Township	
Stream Name		Hazard Classification	
Important Telephone Numbers	Organization	Significant Problems in the Past:	
1.		1.	
2.		2.	
3.		3.	

2. Dam and Embankment

Type of Dam	Height of Dam	Top of Dam El.	Freeboard
Width of Crest	Length of Crest	Upstream Slope	Downstream Slope

3. Spillway

Spillway Type	Spillway Width	Spillway Depth	Spillway Slopes
Crest El.	Crest Width	Crest Depth	Crest Length
Normal Pool EL.	Freeboard	Historic Flow Depth	Date of Historic Flow
Design Capacity	Energy Dissipater	Discharge Channel	Other

4. Outlet (if present)

Type of Outlet	Size of Outlet	Inlet Invert El.
Type of Control	Size of Control	Outlet Invert El.

5. Monitoring Devices (if present)

1.	2.	3.

6. Hydrology and Hydraulic Data

Maximum Capacity	Design Storm Event	Design Storm Flow
Watershed Area	Time of Concentration	

Reservoir Stage-Storage Tables

Elevation	Discharge	Elevation	Discharge	Elevation	Discharge
1.		4.		7.	
2.		5.		8.	
3.		6.		9.	

Reservoir Stage-Discharge Tables

Elevation	Discharge	Elevation	Discharge	Elevation	Discharge
1.		4.		7.	
2.		5.		8.	
3.		6.		9.	

Preparer's Name	Date of Data Sheet

APPENDIX B

REFERENCES

REFERENCES
(Used throughout the manual)

- Arkansas Soil and Water Conservation Commission
  Inspection and Maintenance Manual for Arkansas Dam Owners, 2002
  101 East Capitol, Suite 350
  Little Rock, Arkansas 72201

- Association of State Dam Safety Officials
  Compendium of State Dam safety Inspection Forms, 1997
  450 Old East Vine Street
  Lexington, Kentucky 40507

- Colorado Division of Water Resources, State Engineer's Office
  Dam Safety Manual, 2002
  1313 Sherman Street
  Denver, Colorado 80203

- Department of the Army, U.S. Army Corps of Engineers
  Instrumentation for Concrete Structures, EM 1110-2-4300, 1987
  Washington, D.C. 20314-1000

- Department of the Army, U.S. Army Corps of Engineers
  Evaluation and Repair of Concrete Structures, EM 1110-2-2002, 1995
  Washington, D.C. 20314-1000

- Department of the Army, U.S. Army Corps of Engineers
  Seepage Analysis and Control for Dams, EM 1110-2-1901, 1993
  Washington, D.C. 20314-1000

- Department of the Army, U.S. Army Corps of Engineers
  Seepage Analysis and Control for Dams, EM 1110-2-1901, 1993
  Washington, D.C. 20314-1000

- Department of the Army, U.S. Army Corps of Engineers
  Instrumentation of Embankment Dams and Levees, EM 1110-2-1908, 1995
  Washington, D.C. 20314-1000

- Department of the Army, U.S. Army Corps of Engineers
  Earth and Rock-fill Dams - General Design& Construction Considerations, EM 1110-2-2300, 1994
  Washington, D.C. 20314-1000

- Georgia Department of Natural Resources, Environmental Protection Division
  - Operation, Maintenance and Inspection Procedures for Earthfill Dams
  - Engineering Guidelines, 1998
  4244 International Parkway, Suite 110
  Atlanta, Georgia 30354

- Illinois Department of Natural Resources, Office of Water Resources
  Guidelines and Forms for Inspection of Illinois Dams, 1999
  Springfield, Illinois, 62702

- Indiana Department of Natural Resources, Division of Soil Conservation
  Indiana Handbook for Erosion Control in Developing Areas, 1992
  402 West Washington Street, Room W265
  Indianapolis, Indiana 46204-2748

- Indiana Department of Natural Resources, Division of Water
  - *Dam Safety Guidebook*, 1983
  - *General Guidelines for New Dams and Improvements to Existing Dams in Indiana,* 2001
  402 West Washington Street, Room W264
  Indianapolis, Indiana 46204-2748

- Indiana Department of Natural Resources, Division of Water
  Indiana Drainage Handbook, 1996
  402 West Washington Street, Room W264
  Indianapolis, Indiana 46204-2748

- Indiana Geological Survey
  *Physiographic Divisions of Indiana***,** H.H. Gray, 2000
  Indiana Geological Survey Special Reports, SR61
  611 North Walnut Grove
  Bloomington, IN 47405-2208

- John Wiley & Sons Inc.
  Seepage, Drainage and Flownets, 1989
  Harry R. Cedergren, Author
  605 Third Avenue
  New York, New York 10158

- Kentucky Natural Resources and Environmental Protection Cabinet, Division of Water
  Guidelines for the Geotechnical Investigation and Analysis of Existing Earth Dams
  14 Reilly Road
  Frankfort, Kentucky 40601

- Marks Enterprises, Dan Marks, P.E.
  Remedial Dam Repair: Plant and Animal Penetrations of Earthen Dams
  Arden, North Carolina

- Missouri Department of Natural Resources, Division of Geology and Land Survey
  Engineering Analysis of Dams, 1989
  Maintenance, Inspection, and Operation of Dams in Missouri, 1991
  P.O. Box 250
  Rolla, Missouri 65401

- New Hampshire Department of Environmental Services
  Environmental Fact Sheet s:
  - *Best Management Practices for the Maintenance and Operation of Dams*, 1995
  - *Tree Growth on and Adjacent to Dams*, 1997
  - *Liability and Responsibility of Dam Owners*, 1997
  - *Typical Failure Modes for Dam Spillways*; *Typical Failure Modes of Embankment Dams;* 1997
  6 Hazen Drive, P.O. Box 95
  Concord, New Hampshire 03302-0095

- New Mexico State Engineer Office, Design and Construction Section
  A Dam Owner's Guidance Manual, 1989
  Bataan Memorial Building
  Sante Fe, New Mexico 87503

- New York State Department of Environmental Conservation, Division of Water
  Guidelines for Design of Dams, 1989
  50 Wolf Road
  Albany, New York 12233

- North Carolina Department of Environment and Natural Resources, Division of Land Resources, Land Quality Section
  Dam Operation, Maintenance and Inspection Manual, 1989
  1601 Mail Service Center
  Raleigh, North Carolina 27699-1601

- North Dakota Division State Engineer
  North Dakota Dam Design Handbook, 1985
  900 East Boulevard Ave.
  Bismarck, North Dakota 58505-0850

- Ohio Department of Natural Resources, Division of Water
  Suggested Procedures for Safety Inspections of Dams, 1987
  1939 Fountain Square, Bldg. E-3
  Columbus, Ohio 43224-1336

- Ohio Department of Natural Resources, Division of Water
  Division of Water Fact Sheets
  1939 Fountain Square, Bldg. E-3
  Columbus, Ohio 43224-1336

- Pennsylvania Department of Environmental Protection, Division of Dam Safety
  The Inspection, Maintenance, and Operation of Dams in Pennsylvania, 1999
  P.O. Box 8554
  Harrisburg, Pennsylvania 17105

- Texas Water Commission
  Guidelines for Operation and Maintenance of Dams in Texas, 1990
  P.O. Box 13087
  Austin Texas 78711

- U.S. Department of Agriculture, Forest Service, Soil Conservation Service
  Guide for Safety Evaluation and Periodic Inspection of Existing Dams, 1980
  Washington, D.C. 20013

- U.S. Department of Agriculture, Soil Conservation Service
  Earth Dams and Reservoirs Technical Release No. 60, 1985
  14th and Independence Ave., SW
  Washington D.C. 20250

- U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office
  Prediction of Embankment Dam Breach Parameters DSO-98-004, 1998
  1849 C Street NW
  Washington, D.C. 20240-0001

- U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office
  Training Aids for Dam Safety, Inspection of Embankment Dams
  1849 C Street NW
  Washington, D.C. 20240-0001

- U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office
  Training Aids for Dam Safety, Identification of Material Deficiencies
  1849 C Street NW
  Washington, D.C. 20240-0001

- U.S. Department of the Interior, Bureau of Reclamation
  Safety Evaluation of Existing Dams, 2000
  U.S. Government Printing Office
  Washington, D.C. 20402-9328

- U.S. Department of the Interior, Bureau of Reclamation
  Dams and Public Safety, 1983
  U.S. Government Printing Office
  Denver, Colorado

- U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center
  Guide to Concrete Repair, 1997
  U.S. Government Printing Office
  Washington, D.C. 20402-9328

- Washington State Department of Ecology
  Dam Safety Guidelines, 1992
  P.O. Box 47600
  Olympia, Washington 98504-7600